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On plain carbon steel

Walter Edward Remmers

Department:

ON PLAIN CARBON STEEL

BY

WALTER EDWARD REMMERS

A

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Professor of Metallurgy.

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INTRODUCTION:

In 1921, an investigation was carried on by Messrs. Howe, Foley and Winlock, under the auspices of the National Research Council, the results of which were published under the title of - "Influence of Temperature, Time and Rate of Cooling on Physical Properties of Carbon Steel," by the American Institute of Mining and Metallurgical Engineers, February, 1923. These results showed that all physical properties of a 0.34 C. percent steel are improved by increasing the rate of cooling from temperatures above the critical range up to a certain rapidity beyond which, there is a gain in strength at the expense of ductility and toughness.

The purpose of the first part of this paper is to determine to what extent this is true of steels of drill steel composition. Also, in the above mentioned research, it was found that a C.-0.51 percent steel had its impact resistance gradually increased by increasing the hardening temperature previous to a drawing at 675 degrees C. so that a value of about 24 foot-pounds is obtained by drawing a steel quenched in water from 975 degrees C., whereas, but seven foot-pounds result from a similar drawing of a steel quenched from 910 degrees C. This increase in impact value, shown in the original work, is to be confirmed by testing a number of similar specimens treated in the same manner.

METHODS OF PROCEDURE:

The steel used was of the same lot as used in the original research. Acid open hearth steel was selected because of its greater freedom from impurities. It was cast into 11½ inch square ingots and rolled down to 4 inch square billets by John A. Roebling's Sons Company. These billets were rolled into 7/8 inch round bars by the Carpenter Steel Company. The observations made at the steel mill during the final rolling showed the temperature of the heating furnace to have been 1223 degrees C. to 1260 degrees C. and that the finishing temperature of the bars was within 14 degrees C. plus or minus of 871 degrees C. The Bureau of Standard's confirmations of the results at the steel plant were as follows:-

	STEEL V Percent	STEEL U Percent
Carbon	0.75	0.52
Manganese	0.52 0.54	0.56 0.54
Phosphorus	0.031 0.031	0.031 0.030
Sulphur	0.027	0.029
Silicon	0.11	0.22 0.22

The furnace used is a specially designed vertical, cylindrical, hump-process type manufactured for the original investigation of Messrs. Howe, Foley and Winlock by the Leeds-Northrup Company. The heating element was arranged

so as to give an even temperature throughout the muffle, which was seven inches in diameter and fourteen inches deep.

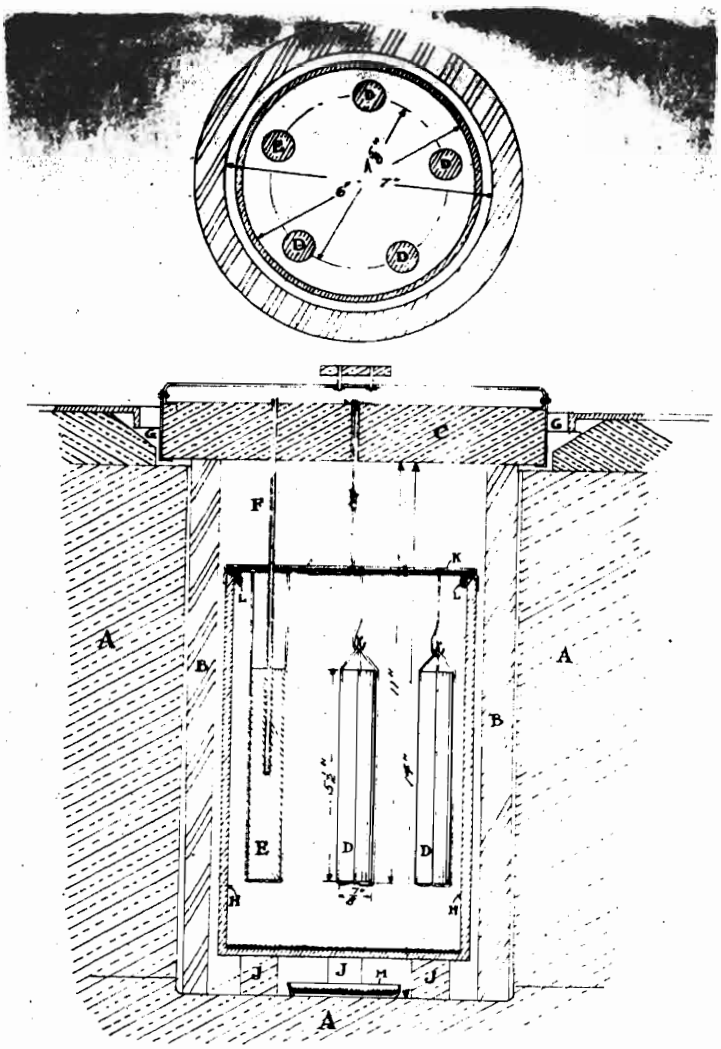


Fig 1.
Furnace showing arrangement of specimens, muffle, etc. in heating chamber.

Figure 1 shows a section through the center line of the furnace containing the sheet iron muffle and with the specimens in position for heating. The sheet iron muffle was used to stop oxidation as far as was possible. "A" is the solid silocel lining - "B" is the heating unit, which consists of a vertical cylinder of refractory material with the resistance

wire embedded in it. "C" is the silocel cover for the furnace; "D", the specimens; "E", a dummy or the same material as the specimens; "F", the thermocouple which has its hot junction at the middle of the length and in the axis of the dummy. "G", an air space facilitating the entry of the cover "C"; "H" is a sheet iron muffle which serves to restrain oxidation of the specimens; "J" are silocel piers to hold the muffle at the desired height; "K" is the muffle cover on which charcoal is spread and from which the specimen and dummy hang, and which, in turn, is suspended from the furnace cover. "M" is a small pan of charcoal to take up oxygen from the heating chamber. Fig. 2 shows the furnace during a heating, and Figure 3 shows the heat-insulation opened. This lining was supported on the hinged shell so it could be readily thrown back. The furnace is heated entirely from the side, the top and bottom being heated only by radiation and convection, therefore the ends tend to be materially colder than the middle. To offset this defect, the manufacturers set the heating wires closer toward the ends than

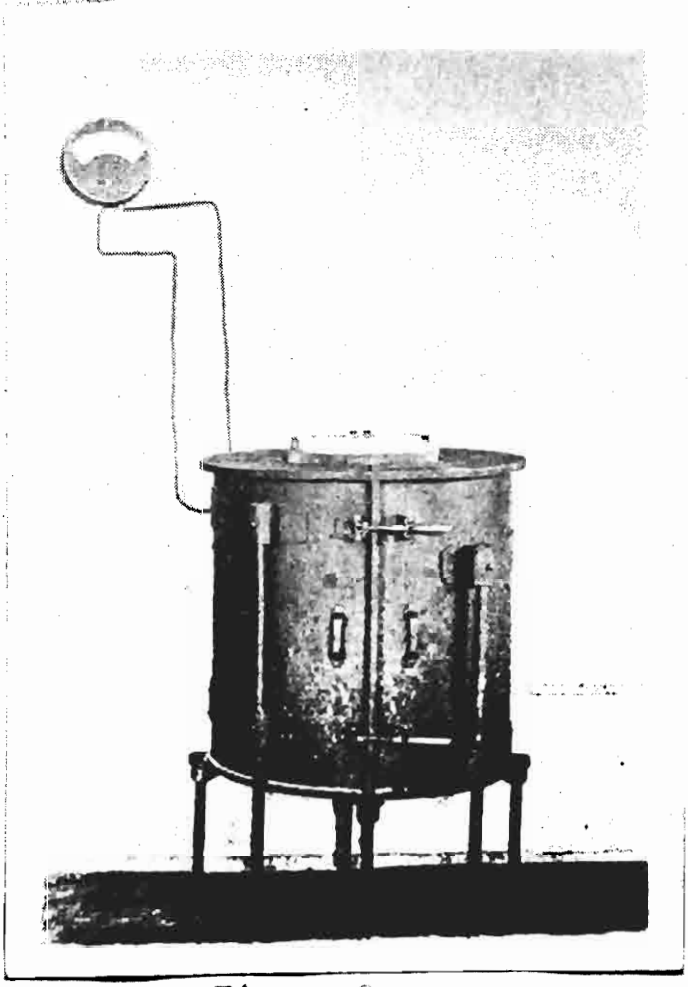


Figure 2.

in the middle of the length of the heating muffle. And because this end cooling effect decreases towards the middle of the length, the heating chamber was made much longer than the specimens to be heated, 14 inches against 5½ inches.

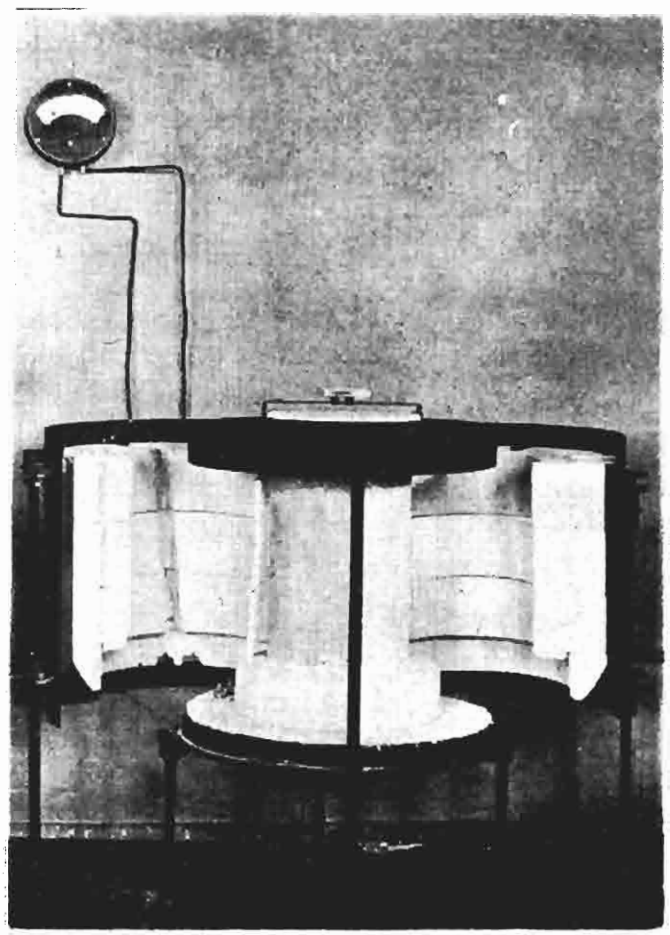


Figure 3.

As for the tensile specimens, it is only the middle two-inch measured part that is of importance, so that in the latter, the ratio of the length of the heating chamber to the length of the specimen to be uniformly heated, is seven. In order to place the measured length of the specimen during heating where the temperature is most even, it is important to determine the thermal gradient of the furnace.

By the method shown in Figure 4, the thermal gradient was determined. The heating chamber is brought to a temperature within a range that includes practically all the heats and the current adjusted so that the temperature would rise very slowly. The specimens were inserted in their regular place because they tend to equalize the temperature by their thermal

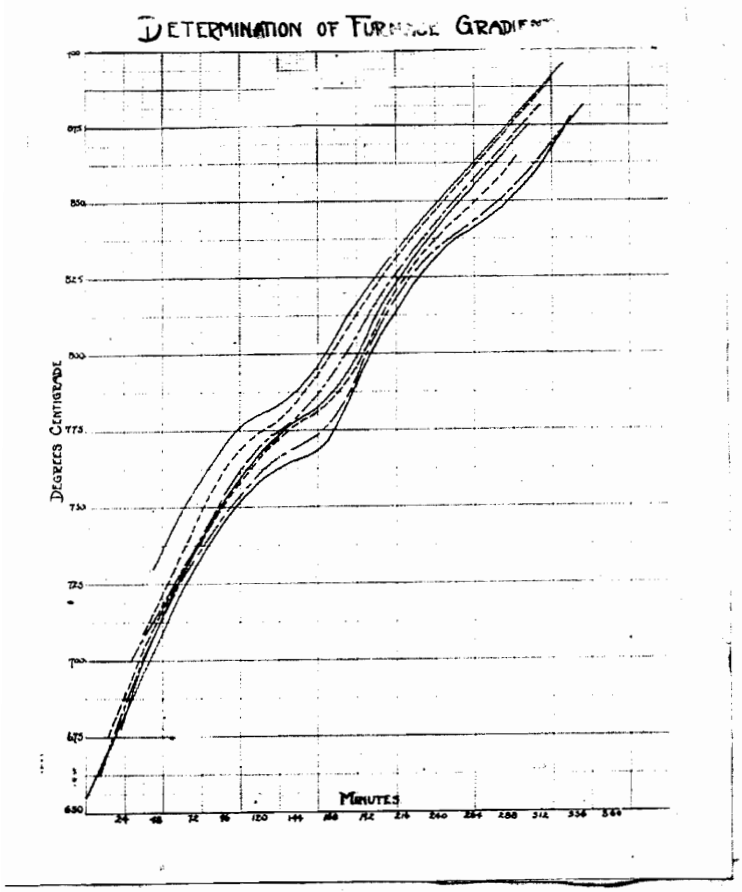


Figure 4.

conductivity. To determine the thermal gradient, the thermocouple was inserted for one inch into a two inch length of the round bar and lowered in the line usually occupied by the dummy, to within two inches of the bottom and held there for ten minutes to allow it to come to temperature, when a record of the time and temperature was made. It was then raised to points one inch apart and the time and temperature recorded after a ten minute stop at each. This operation was repeated, re-determining the temperature and recording the time at a series of points as many times as seemed desirable. At each of the redetermined points, the temperature was somewhat higher than before. Thus a number of time-temperature points were determined for each inch of the explored line and were plotted as in Figure 4, each line denoting a definite distance from the bottom of the muffle.

From this diagram, the thermal gradient that existed at any given moment was derived, as in Figure 5, by plotting in a diagram, with the distances from the bottom of the furnace

as abscissae and the temperatures as ordinates, the intersection of the ordinate of time with the several position lines in Figure 4.

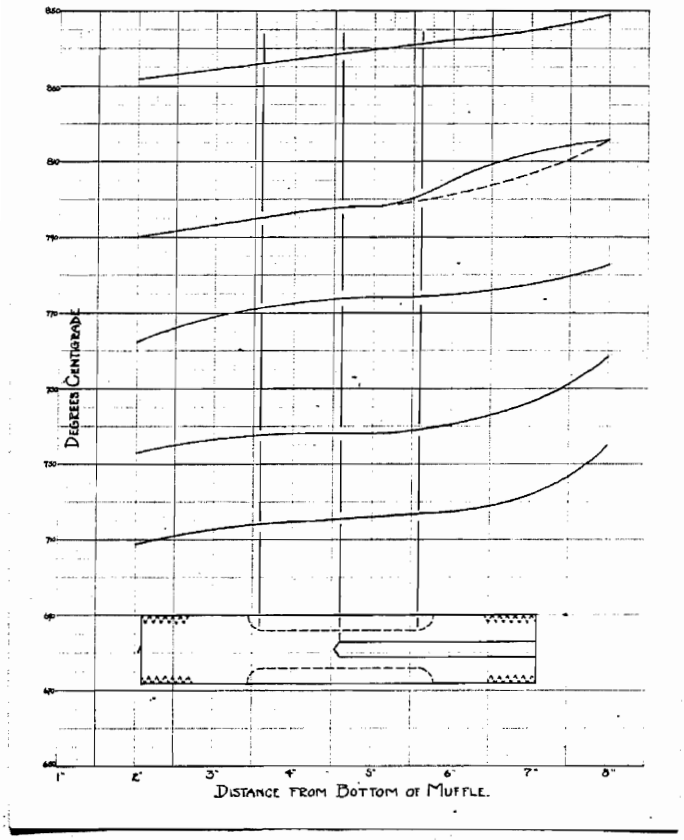


Figure 5.

At first, it was intended that an alumel-chromel thermocouple of No. 20 wire be used for measuring temperatures. This was used in a drawn quartz tube, but such a couple proved to be unsatisfactory, because in every case there was an appreciable lowering of the e.m.f. for a given temperature. A similar couple of No. 14 wire was then tried, with the idea that perhaps any slight contamination would have a much less effect in the decalibration of couple of greater mass. This couple proved satisfactory for some time, but it also gradually dropped in e.m.f. value for a definite temperature. Also the silica protecting tube started to decompose. This might be explained by an extract from the U. S. Bureau of Standards Technologic Paper No. 170:-

"Fused quartz is pervious to hydrogen and other reducing gases. Any reducing gas within the protecting tube of a rare-metal couple is disastrous, particularly when the tube contains silica. The silica is reduced to silicon which is readily absorbed by the platinum. Above 1050 degrees C. and even at lower temperatures after prolonged heating, quartz devitrifies and crumples away."

The thermocouple was not a rare-metal couple in the above case but whether silicon has any effect on the decalibration of a base-metal couple was not determined. The subject of thermocouples in this work, offered an interesting problem for investigation, but as time would not permit, a suitable couple had to be obtained and the heat-treating continued.

The couple which was ultimately used was a platinum-platinum rhodium couple encased in an alundum tube with an outside glaze capable of withstanding 1300 degrees C. The alundum tube was encased in a graphite sheath for standardization in the three molten metals: lead, zinc and aluminum, and a fourth value, the boiling point of water was also determined.

Again quoting the Bureau of Standards Paper No. 170: "Graphite tubes afford an excellent protection to quartz or porcelain tubes on rare-metal couples and are frequently used with base-metal couples for molten metals. Porcelain encased in a sheath of graphite can be used in molten aluminum."

The four points obtained were then substituted in the formula: $\text{Log}E = N\text{Log}T + \text{Log}M$, The curve was plotted from the calculated values.

E = e.m.f. generated.

N and M = constants.

T = temperature in degrees C.

All couples used, were standardized with the Leeds and Northrup portable potentiometer which was used in taking the readings during the heat treatments. The calibration was checked at intervals and the temperature of Ac_1 was noted in each heating. Figure 6 is the average rate of heating, which was closely followed.

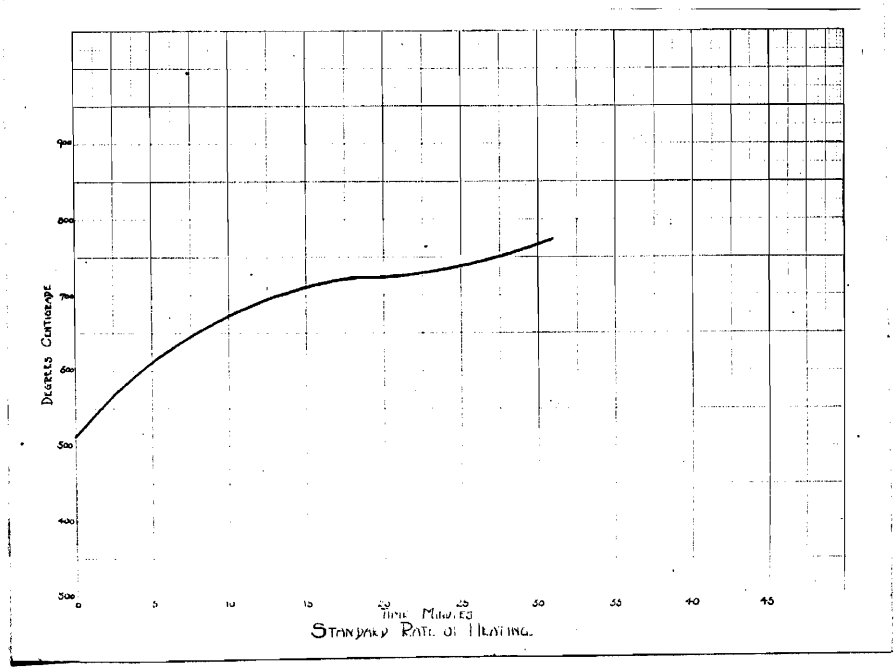


Figure 6.

When using a base-metal couple, the potentiometer was set at even 0.5 millivolts in advance of the fall in e.m.f. and the time was observed when the galvanometer indicated a balance. The same observations were made during heating, except when passing through Ac and also through Ar, when readings were taken for every increment or decrement, as the case may be, of 0.1 millivolts. In using the noble-metal couple, readings were made every 0.2 millivolts, and during Ac and Ar, every 0.02 millivolts. On quenched specimens, no attempt was made to record a cooling rate. The water was

vigorously stirred before quenching after it had been determined that the water continued to circulate for at least two minutes afterward.

The procedure on heating was to raise the furnace to about 600 degrees C; cover the bottom of the sheet iron muffle, which had been heated within the furnace, with charcoal and sprinkle a layer of charcoal on the sheet iron muffle lid which supported the specimens. The furnace cover, which was replaced, was the one which supported the specimens. The current flowing through the furnace element was 12.5 amperes.

The experiments on the C.-0.75 steels consisted of heating at a constant rate to 10 degrees C. above Ac_3 and holding at that temperature for a definite time and then cooling according to various rates. The periods at Tmax. were 20 minutes, 1 hour and 2 hours. All specimens were normalized by heating to 871 degrees C. and air cooling previous to performing the experiments. Various methods of cooling were also made from the annealing temperature, namely: air, powdered lime and furnace. (See figures 7 and 8). On C.-0.52 steels, the bars were normalized as before. These experiments consisted of heating to different temperatures, 75 degrees C. 205 degrees C. and 270 degrees C. above Ac_3 and quenching. These specimens were then drawn at 450 degrees C. for 30 minutes and 675 degrees C. for ten minutes. A bar was examined in the quenched condition from each of the three quenching temperatures.

The following letters were used to represent the mode

of cooling and the approximate rate:

A, Double retarded furnace cool. - 0.°01 C. per second.

C, Plain furnace cool. - 0.°05 C. per second.

E, Retarded air cool. - 0.°60 C, per second.

F, Plain air cool. - 0.°90 C. per second.

G, Accelerated air cool. - 1.°10 C. per second.

L, Powdered lime cool. - 0.°28 C. per second.

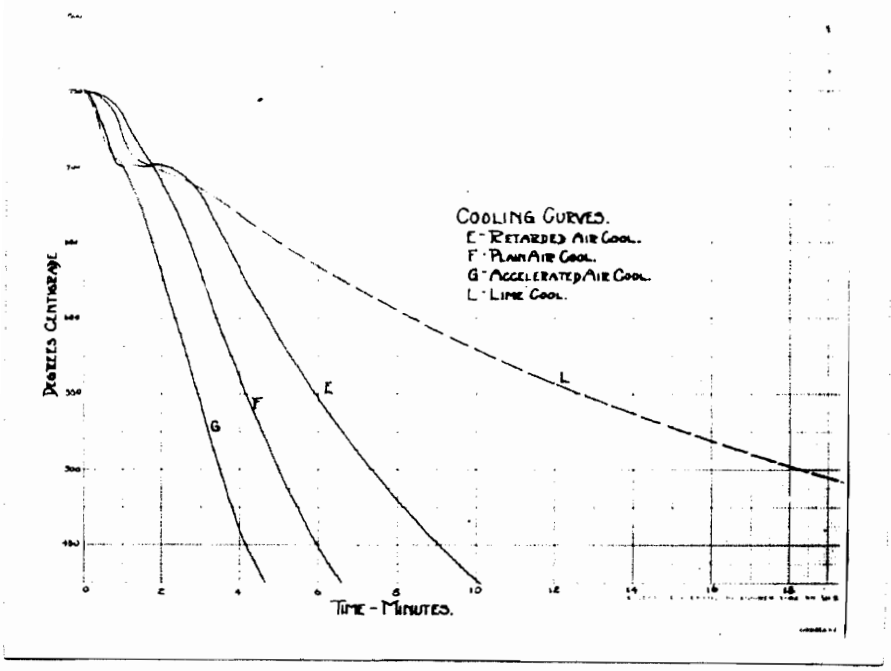


Figure 7.

In the double retarded furnace cool, considerable current was left in. This amount was predetermined so as to give an approximate rate of 0.°01 C. per second through Ar. In the retarded air cool, the sheet iron muffle, which was fastened to the lid, was withdrawn with the specimens and allowed to cool suspended in the air. For an accelerated air cool, the specimens were suspended from the support and cooled by a current of air from a fan as shown in Figure 9.

The temperature used in the first part of the work was 10 degrees C. above Ac_3 and in the second part 75° C, 205° C. and 270° C. above Ac_3. The Ac_3 for C.-0.75 percent was taken

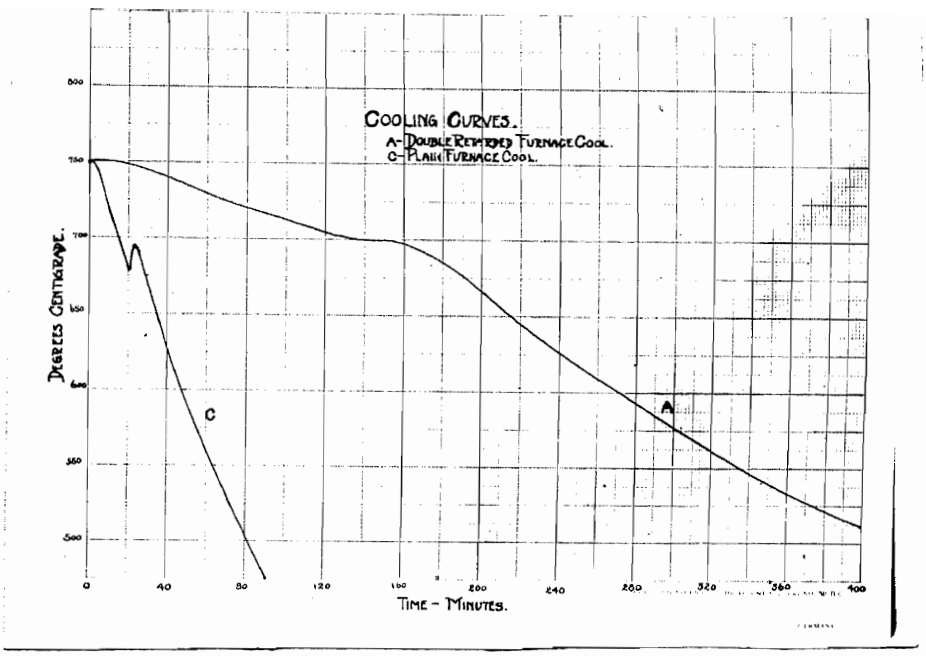


Figure 8.

to be 741° C. and for C.-0.52 per cent, 770° C. These temperatures were taken from the original work of Messrs. Howe, Foley and Winlock.

The time of holding at T. max. was 30 minutes when normalizing, and 20 minutes, 1 hour and 2 hours at T.max. for the experiments on C.-0.75 per cent steels. The hold at

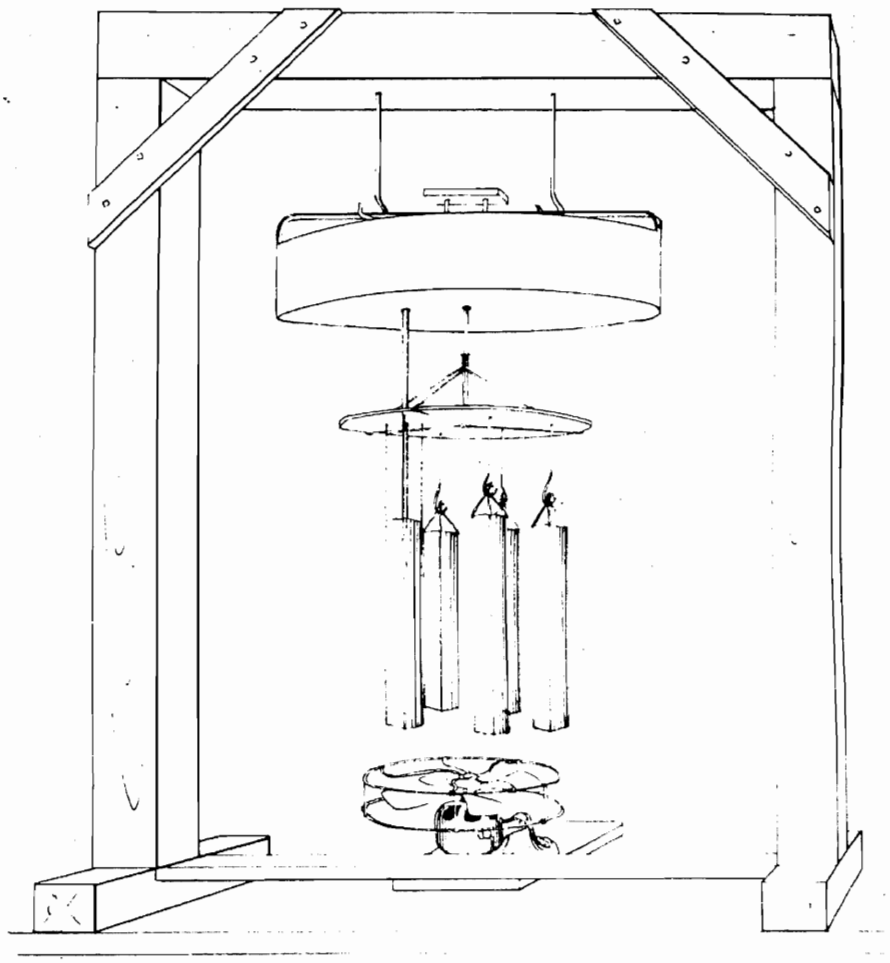


Fig. 9.
Showing method of suspending specimens during air cooling.

T.max. before quenching the C.-0.52 percent steels was ten minutes and the time at the drawing temperature was ten minutes in some cases and thirty in others, as indicated in the tabulations.

The test pieces were all machined according to A.S.T.M. specifications, Figures 10 and 11. In reducing the diameter to 0.505 inch, the outer 0.185 inch was removed. This should include all decarburized or oxidized portions, should there be any resulting from the heat treatment. The tensile properties and hardness were determined by Tom W. Greene under the supervision of R. S. Johnston of the Bureau of Standards. A small Emery hydraulic testing machine of 230,000 pound capacity was used for this purpose and the specimens were carefully centered in the machine grips before any stress was applied. The elongation on the two inch gage length was measured by a Ewing extensometer. The proportional limit was determined from the stress-strain diagram as that stress at which the ratio of unit stress to unit deformation ceases to be constant. The yield point was determined by the drop of the beam of the testing machine. As the Emery machine is extremely sensitive, the yield point values are probably very accurate. The tensile strength was determined by observing the maximum load carried by the specimen before rupture occurred. The proportional limit, yield point and tensile strength values are based on the original

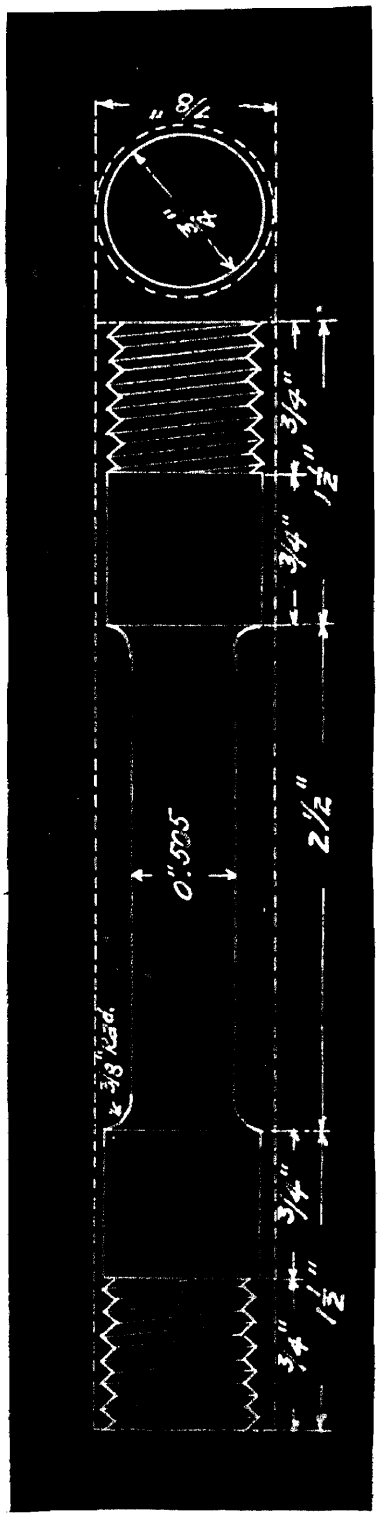


Figure 10. Tensile Bar.

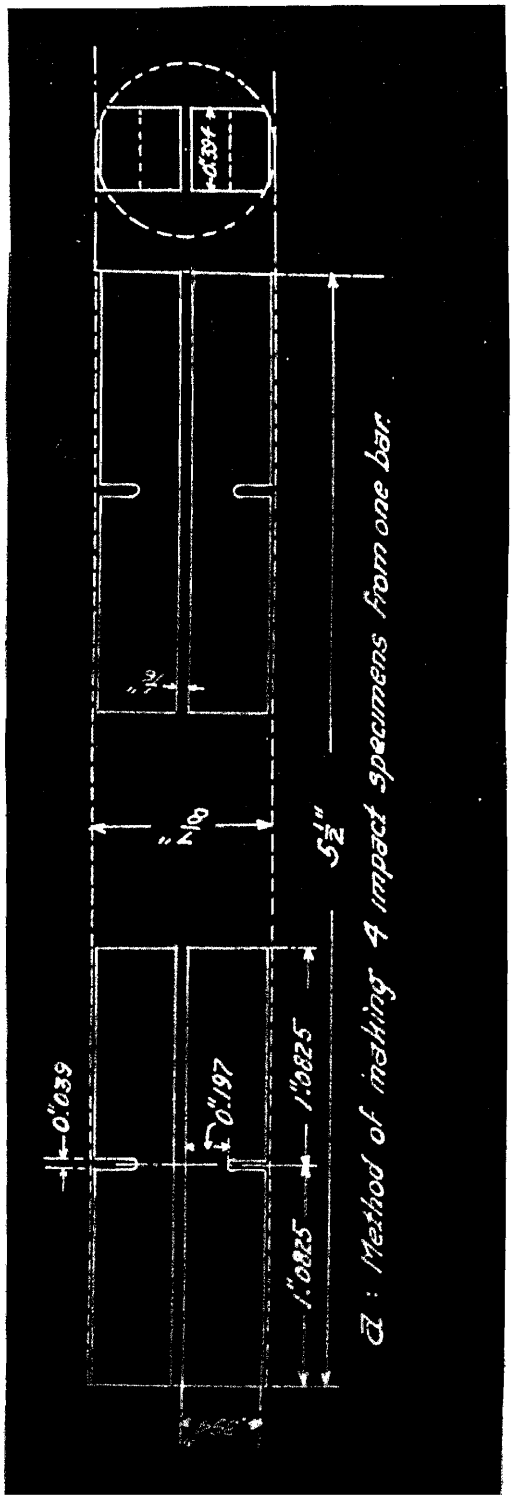


Figure 11.

cross-sectional area of the specimens.

The impact specimens were broken at the Watertown Arsenal under the direction of Dr. F. C. Langenberg. The method of cutting four specimens from a bar as shown in Figure 11 was used. The outside corners are slightly rounded but since this portion is on the notched side, it has no effect on the results. The middle portion of these bars was used for microscopic examination.

Since the equipment used was the same as that used in the original work, and since the method of procedure of Messrs. Howe, Foley and Winlock was attempted to be followed very closely, the description of these was taken almost directly, with but slight changes, from their paper, as no explanation could be prepared better than that of the originators themselves.

RESULTS.

Part 1 - C.-0.75 Percent Steel.

This part of the paper will deal entirely with the results of the work on the C.-C.75 percent steel. It will be noticed from Figures 12, 13 and 15 that the proportional limit, tensile strength and Brinell hardness all increase with an increase in cooling rate, and do not reach a maximum at any rate slower than accelerated air, about 1.°095 C. per second. Therefore, the critical rate lies somewhere beyond, attained by a faster cool. The elongation and reduction in area decrease with an increase in cooling rate, Figure 14.

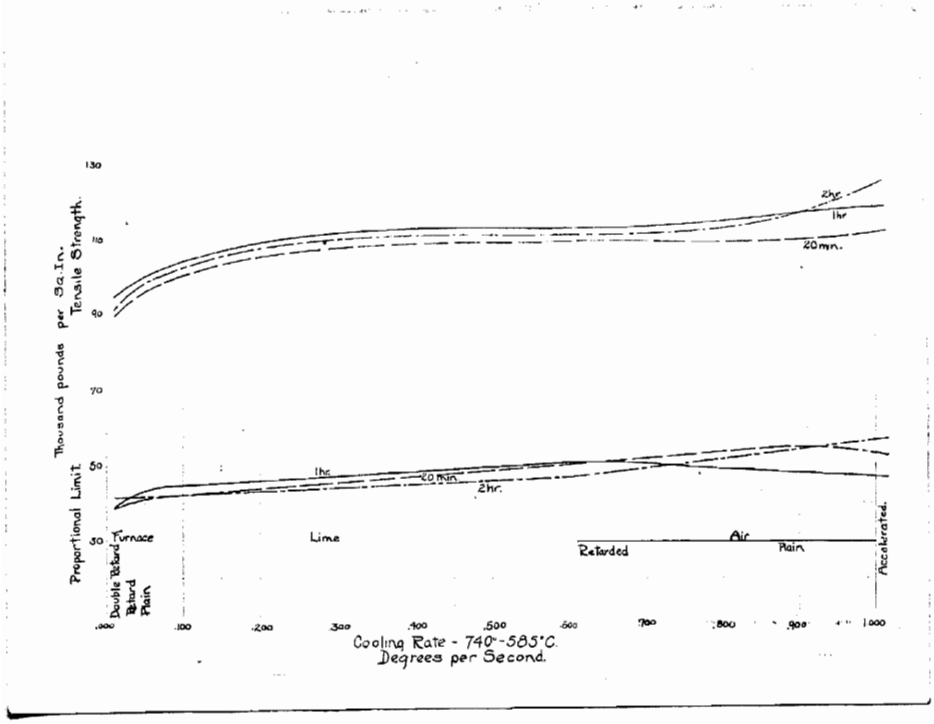


Figure 12.

In Figure 13, it will be noted that the Charpy impact values tend to show a maximum around a cooling rate of 0.°75 to 0.°85 C. per second. This would be a plain air cool. Some of the curves show a slight waver from the uniform but these might be termed "freaks", as they are not normal, probably due to

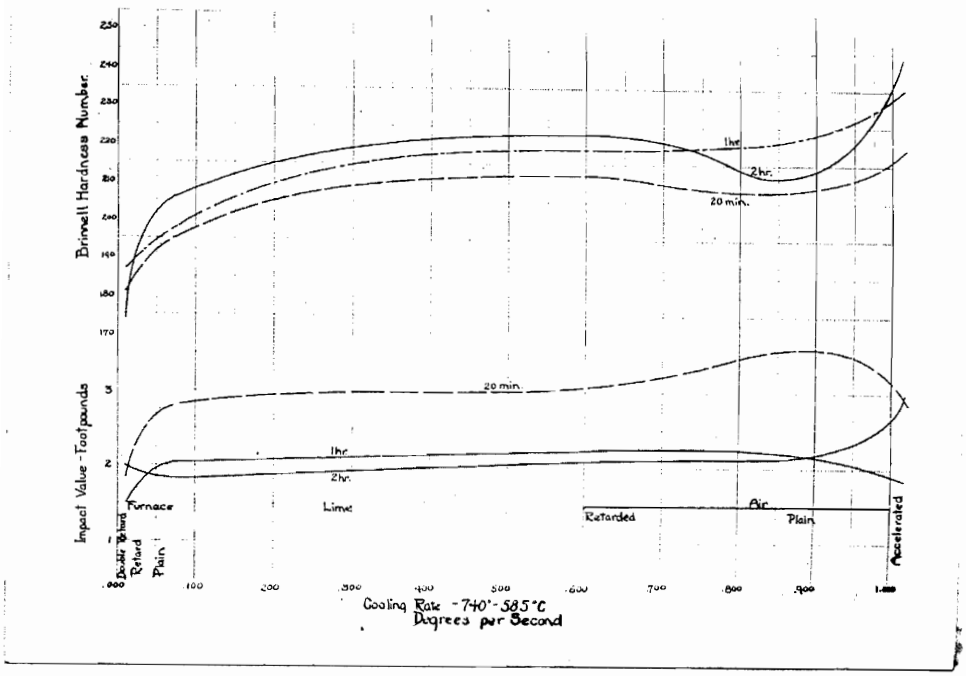


Figure 13.

experimental error. An explanation will be offered for the great changes in the slope of all the curves within the range of furnace cooling later.

The difference in degrees per second is small and the change in physical properties, which is large, might be explained by grain growth.

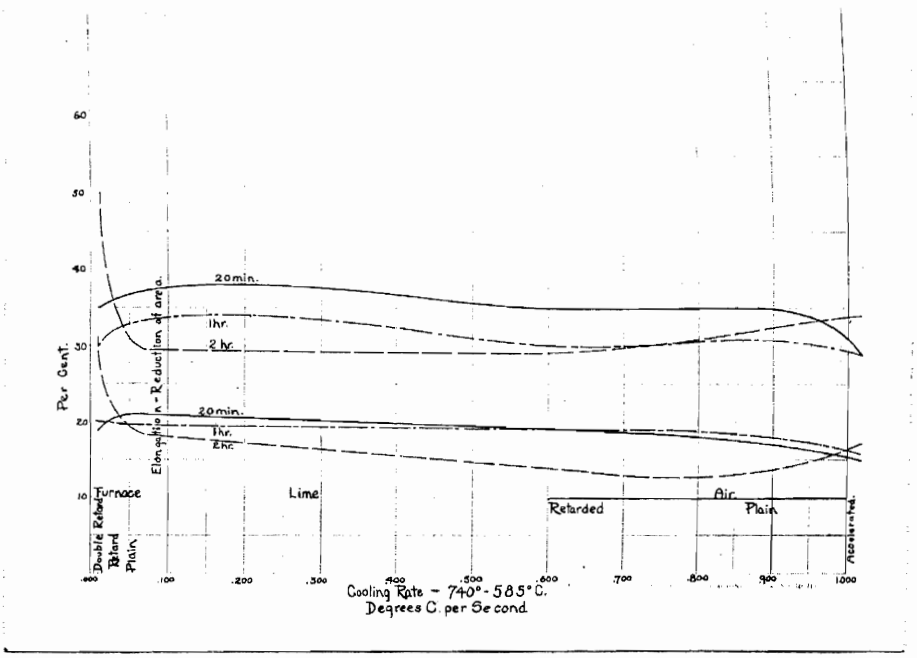
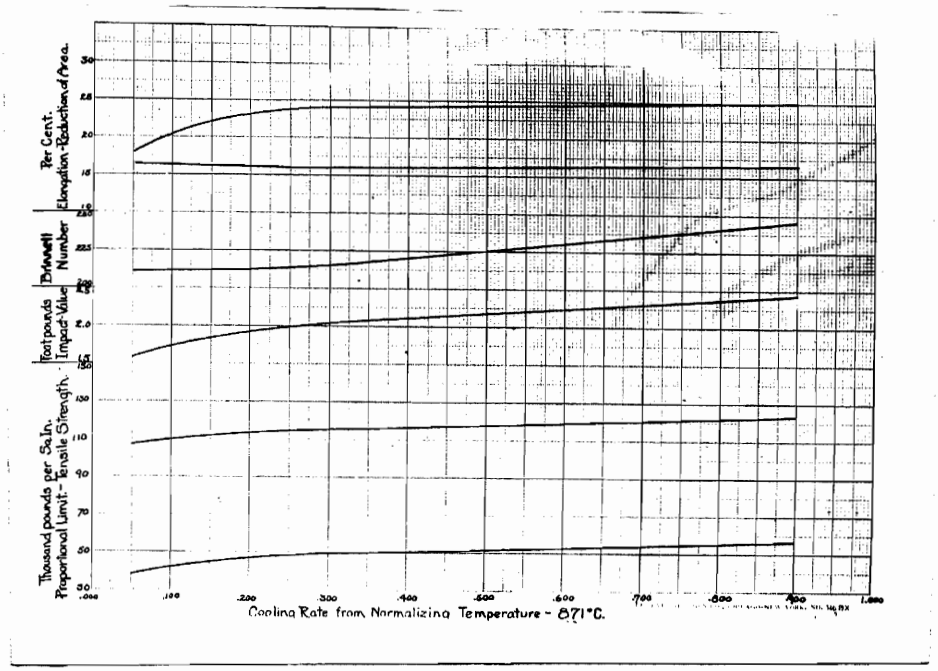


Figure 14.

F. B. Foley has derived some empirical formulas for calculating the physical properties from the curves obtained in previous work of this same nature. These formulae were used for calculating the values for the various rates used here, and the calculated values are



tabulated in Table 1 with the observed values and per-cent of observed value difference.

The formulae of Foley are as follows:-

Figure 15.

$PL = 24{,}750\ (1 + c) + [(115{,}225c - 101{,}100c^2 - 12{,}250) \cdot \sqrt[3]{R}]$

$YP = 25{,}000\ (1 + c) + [(89{,}680c - 36{,}185c^2 - 8{,}080) \cdot \sqrt[3]{R}]$

$TS = 50{,}000\ (1 + c) + [(7{,}023 - 11{,}450c \quad 50{,}780c^2) \cdot \sqrt[3]{R}$

$SR = 118{,}000 \quad 33{,}200\ \sqrt{R}$

$Ext. = 52.1 - 61.4c + 22.4c^2$

$Con. = (79 - 61c)\ R^{.05}$

$I = (51.25 - 111.5c + 64.27c^2)\ R^{.29}$

$B = (97 + 80c) + 100c \quad \sqrt[5]{R}$

Where:-

PL = proportional limit.

YP = yield point.

TS = tensile strength.

I = impact resistance, foot-pounds per sq. in. (Charpy).

B = Brinell hardness.

c = percent carbon.

R = rate of cooling ^{o}C per sec. between Ac_3 and 585^{o} C.

SR = stress at rupture.

Ext. = percent extension in two inches.

Con. = percent contraction of area.

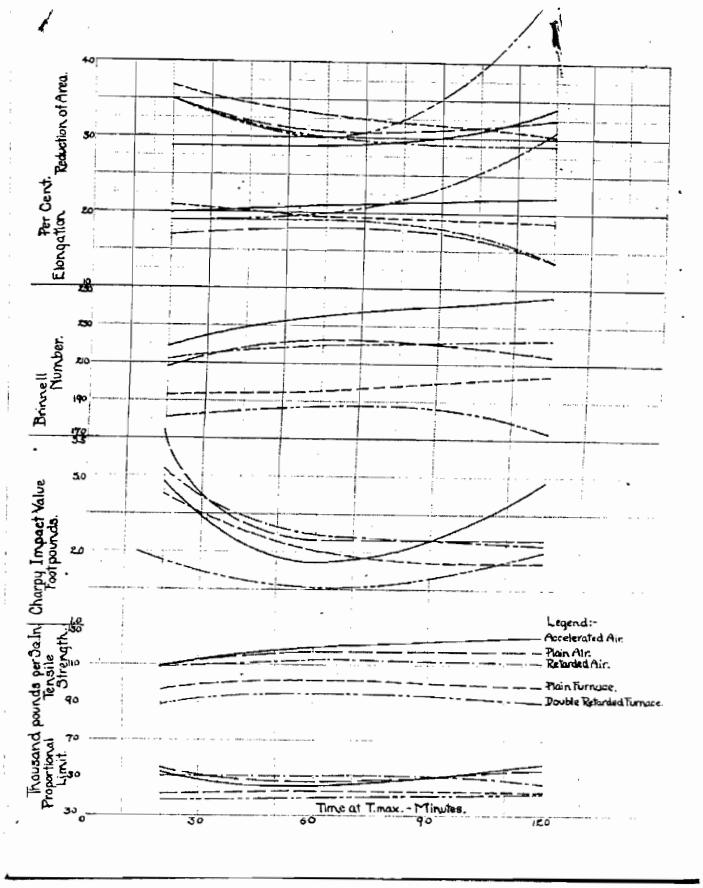


Figure 16.

The increased holding, that is, two hours at T. max., either showed no gain in physical properties or a decrease, Figure 16.

In the microscopic examination of these specimens, some very striking examples of Colonel Baliew's explanation of uniform width of pearlite lamellae were found. Figure 17 shows the plates at two different incident angles, (see following page).

Figure 17.

DISCUSSION OF RESULTS.
Part 1.

Upon microscopic analysis, all of the specimens showed pearlite with a gradual decrease of globular cementite from approximately 100 per cent spheroidized by the double retarded furnace cool after a two hour hold at T. max., to a very small percentage of globular cementite in the more rapid cools, such as accelerated air cooling. See Figures 47 to 61. It is also shown that the amount of spheroidation is dependent on the time held at T.max; the longer the hold the more globular cementite.

The proportional limit increased with increase in rapidity of cooling through the rates used. It appears that the different periods at T.max. had but little influence on the value of the proportional limit, as there is considerable crossing back and forth in the curves shown in Figure 12. The yield point follows the values for proportional limit throughout.

Tensile strength is increased by the faster cooling rates. The one hour hold at T.max. gave better tensile strength than either the two hour or the twenty minute hold and the two hour gave better tensile properties than the twenty minute. In the case of the accelerated air cool, the two hour hold resulted in better tensile strength than the one hour hold. This is contrary to the original work on C.-0.34 steel.

The stress at rupture increased with an increase in cooling rate, the time at T.max. again showing very slight effect on the values of stress at rupture.

With the exception of a very slow cool, the extension is decreased with an increase in cooling rate and also by an increase in time of holding at T.max. This differs from

the lower carbon steels where there is no variation in extension for various cooling rates. This decrease in extension agrees in general with the values for the same steel, and same T.max. as illustrated in the paper of Howe, Foley and Winlock.

In all cases, except the very slow cooling, the rate had practically no effect on the reduction in area but, an increased hold at T.max. decreased it. It might be well to note the exceedingly large value obtained for the reduction of area and the elongation for the two hour hold and then a double retarded furnace cool. Upon inquiry, the Bureau of Standards verified these values.

As to Charpy impact values, the slight rise in the values at a rate approximately a plain air cool might be taken as a maximum, as there is a decided drop with increased rates. A peculiarity to be noted here is that the two hour hold for various cooling rates gives a line which curves in the opposite direction from those of the one hour and twenty minute holds.

Both Brinell and scleroscope hardness tests were made. In this series of heat treatments little attention was paid to the scleroscope values, as an average of twenty readings made on the perpendicular diameters of the cross-section of the specimens gave values which checked very closely with the Brinell values. The Brinell hardness number increases with an increase in cooling rate; also the hardness number increases with an increased hold at T.max. In the previous work of this nature by Howe, Foley and Winlock, it was believed

that time at T.max. had no effect on the hardness. The increase shown by these results, however, is very slight.

The curves of the physical properties as shown in Figure 15 agree very well with the general results of the work. These curves illustrate values obtained for three rates of cooling from the normalizing temperature, 871° C., namely, air, lime and plain furnace. The values all increase uniformly with an increase in cooling rate with the exception of elongation, which remains practically unchanged.

As is known, time at T.max. influences both the diffusion and the grain growth, also the amount of spheroidized cementite as is shown in the accompanying microphotographs. It is shown that increasing the time at T.max. produces better tensile strength, greater proportional limit, larger Brinell hardness number, smaller elongation, smaller reduction of area and fewer foot-pounds for the Charpy impact value. This is true up to a hold of about one hour, probably slightly less than one hour. After this critical hold has been passed, the reverse is true. This critical hold is not as noticeable on some properties as upon others; for instance, Brinell hardness number tends to maintain its original slope and continue to increase with increased time at T.max. just as there is a tendency for the impact value to continue to decrease.

It is generally accepted that grain growth and diffusion are opposite in their effects upon the physical properties of a steel. - The diffusion being beneficial and grain growth

detrimental. However, in the case of a C.-0.75 per cent steel which is almost of eutectoid composition, slightly above 90% pearlite, the proeutectoid constituent has little effect. In other words, the grain growth of the excess ferrite has no appreciable effect on the resulting physical properties. Therefore, the resulting properties are dependent on the state of the pearlite and the diffusion. The accompanying Figure 18, after Sauveur, shows that at C.-0.415 percent the amounts of pearlite and proeutectoid ferrite are equal and, as the amount of carbon increases, the influence of the excess ferrite grain size is lessened and lessened.

When steel is heated above its critical range and is in the austenitic state, two things are taking place, the austenite grains are coalescing and the impurities, principally carbon, are diffusing.

Coalescing is considered as a rotation in place of the grains until a position common to both is met.

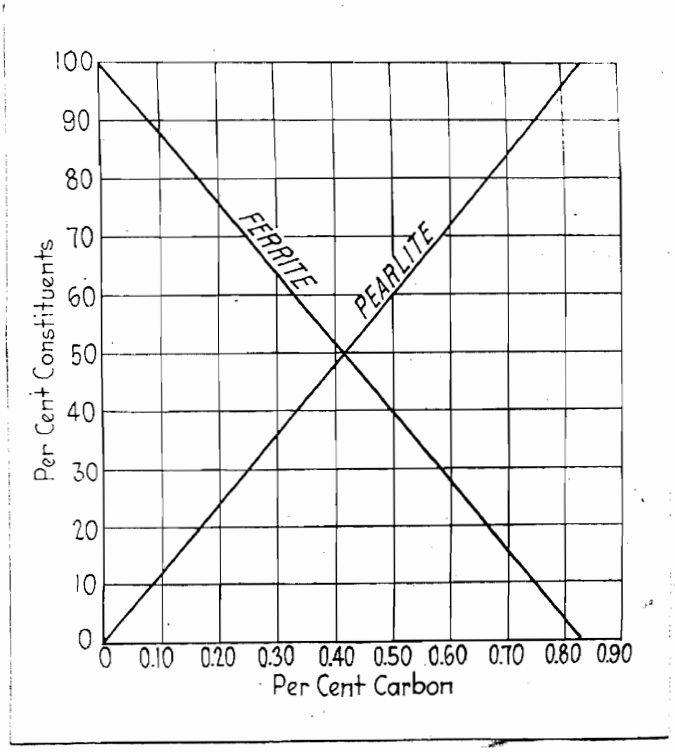


Figure 18.

Diffusion is a dissemination of the impurities, the rate

of which is dependent on the temperature and differences in concentration. The completeness of diffusion or the state of homogeneity is controlled by time. Diffusion differs from grain growth in that, in diffusion there is a migration, whereas, in grain growth, the change is merely a swinging about in the same position. Grain growth is dependent on time and temperature. It must be remembered that heat treatment alone is here considered and other factors which influence grain growth such as previous cold work and grain size contrast are neglected. Upon cooling, when the gamma to alpha change takes place, there is a fragmentation of the original grain and many "grainlets", as Bain calls them, are formed. These grainlets then proceed to coalesce. The original austenite grain persists in steels other than eutectoid composition in that on cooling through the critical range the proeutectoid constituent is rejected to the grain boundary. This is then known as the network and not as grain size. Grain growth, then, is not an increase in the size of the network but of the grains that compose it.

The proeutectoid ferrite is not sufficient to form a network but is rejected into very small areas. Its small quantity would therefore have little effect on physical properties, as the effects of the state of the pearlite would outbalance any effects of the excess constituent. The pearlite decreases in size from a widely lamellar to finely lamellar, with increase in rate of cool. It will be noticed

from the accompanying photomicrographs that the longer the hold at T.max., the greater will be the amount of spheroidized cementite. It may be, that in the case of the shorter holds at T.max. that diffusion has not been carried to completeness and that the flat carbon rich plates still persist to some extent. The question is then raised as to whether spheroidized cementite is a primary condition or whether it is a globularizing of a lamella which was primary. Also, is it more easy for cementite to globularize from a very homogeneous condition of finely dispersed carbide than from a plate?

In the case of almost total spheroidation, grain growth must be taken into account, however, because the free ferrite is by far the excess constituent. On a very slow cool, grain growth would be excessive. The radical change of slope to the opposite direction of the physical property curves might be attributed to this. It is very noticeable on the retarded furnace cool specimens, and the excessive values for extension and reduction of area obtained on this cool may be explained by the large grain growth.

It would be difficult to state the time at which diffusion is complete but this is unimportant, as the critical time is that time at which the detrimental effects are of sufficient values to cause a decrease in the values that are benefitted by diffusion.

CONCLUSIONS - Part 1.

All physical properties are improved with an increase in cooling rate from above Ac_3 within the range of heat treatments made, which extended to an accelerated air cool about 1°09 C. per second, resulting in a very fine pearlite. This is attributed to the fine state of the pearlite.

Increasing the time of holding above Ac_3 up to a period slightly less than an hour is beneficial - beyond that, detrimental. This is where the resultant structure is lamellar pearlite; when the cementite becomes globular and free ferrite is predominant, the rapid grain growth soon outweighs the benefits of diffusion. The critical time for steel of this composition, C.-C.75 per cent, is higher than for the lower carbon, slightly less than an hour as compared with a period somewhere between ten and thirty minutes. This is reasonable because there is such a very small amount of free ferrite that it takes a considerable time before the beneficial results of diffusion are overcome by the effects of grain growth.

RESULTS.

Part 2 - C.-0.52 Per Cent Steel.

The second part of the problem was to determine the soundness of the previously determined results obtained on C.-0.52 per cent steel when quenched from temperatures above Ac_3 and drawn. It was found that an impact value of about 24 footpounds was obtained by drawing a steel quenched in water from 975° C. whereas but seven footpounds result from similarly drawing a steel quenched from 910° C.

The same equipment and procedure was used as in the preceding work. The water in which the specimens were quenched was stirred violently and then the period for which it continued to circulate, was determined. This was found to be over two minutes, which was longer than required.

To the question:- Do the results of this work check those of the previous determination?- the answer is the affirmative. And further, higher quenching temperatures were used and it was found that at about 1000° C. appeared to be the critical temperature; higher quenching temperatures resulting in a decrease in impact value as shown in Figure 19. The quenching temperature has little effect on the Brinell hardness number.

In the accompanying photomicrographs, a longitudinal specimen of both the C.-0.75 per cent and 0.52 per cent appear with the banded ferrite showing. In the customary practice of polishing a cross section of a piece of rolled metal, these fibers of segregated ferrite are frequently over-

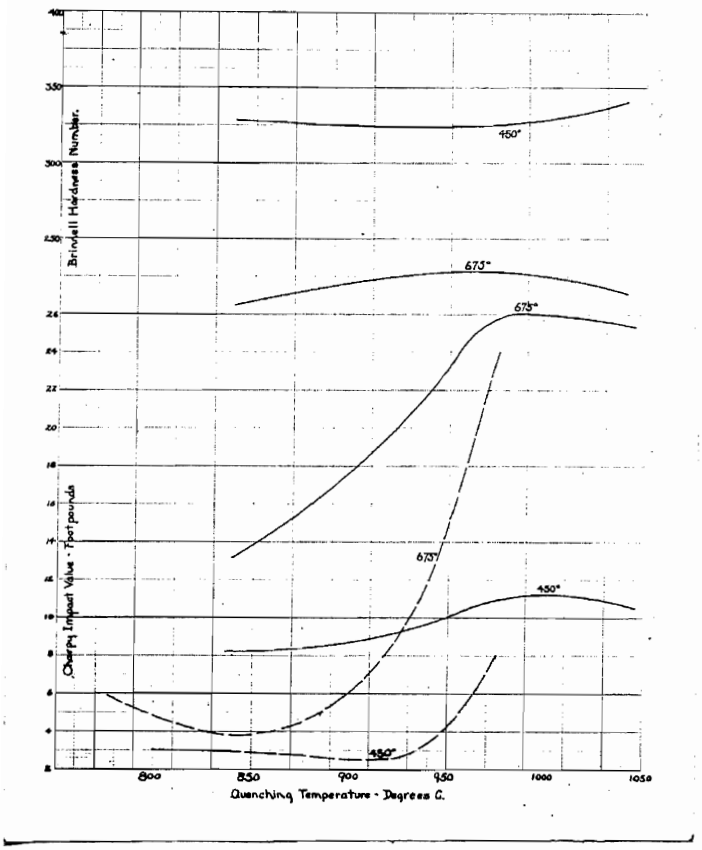


Figure 19.

looked. The annealed structure appears very much like the original.

The quenched and drawn specimens all show a very fine sorbite. Also in these specimens persists the directional influence of the martensitic orientation, see Figures 75 to 80, at 2000 diameters. In Figure 68, the grain boundaries of the austenite which superseded are easily discernible. This specimen shows a troosto-sorbite with much martensitic influence remaining. This also gave the lowest impact value. In Figure 78, the specimen was quenched after a ten minute hold at 975° C. and then drawn at 675° C. for ten minutes. This showed practically no martensitic orientation remaining and gave the highest impact value. It is peculiar to note that, not considering the difference in carbon content of the two, the highest impact value and some of the lowest impact values are from structure of exactly the same nature, the only difference being in the size of the cementite globules in the ferrite matrix. Homogeneity may here again be recognized as a most important factor with reference to impact value. The specimens showing the martensitic influence are very definitely segregated.

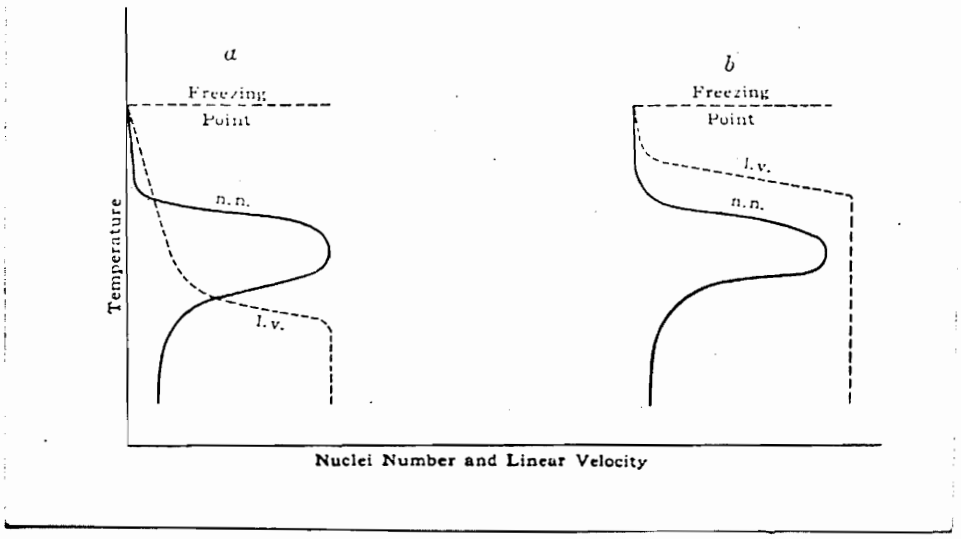


Figure 20.

DISCUSSION OF RESULTS - Part 2.

The fineness of the structure may be explained by Hoyt's explanation, Figure 20. By plotting both nuclei number and linear velocity on one ordinate and temperature on the other, curves of two types may be obtained "a" and "b". It is known that most metals crystallize according to the latter. That is, when a metal above its freezing point or recrystallization temperature is slowly cooled, as it drops below the phase change line, nuclei number has a small value and linear velocity is increasingly large, resulting in very large crystals. A rapid cool will carry the metal down to temperatures where the nuclei number value is very high before time has elapsed for the necessary linear crystallization. This would give a high nuclei number and a rapid linear crystallization, which would result in a very fine grain structure.

Specimens of the quenched bars were polished and etched, Figures 65 to 67. Macroscopically, the surface was composed of two annulets. In the quench from the lower temperature, a shell of about two millimeters thickness appeared all around the specimen.. This shell was not nearly attacked as readily as the center portion which was troostite. In the next higher quench, the outer shell increased in thickness to about half the radius of the bar and in the highest quench, the entire section was attacked very slowly showing martensite. When the word martensite or troostite is here used, a perfectly homogeneous structure of either one is not meant but the larger part is of that structure. Perhaps the words troostitic and martensitic would be far more descriptive in this case. In a series of scleroscope hardness tests made on the surfaces of these pieces, a very decided change is noted at the boundary between the two, which was gradual for the distance of one to two millimeters. The more rapidly attacked troostitic structure being softer than the less rapidly attacked.

Along these lines, the work of Portevin and Garvin is extremely interesting. By assembling a very sensitive recording apparatus, they determined two breaks in the thermal curve on a quenched specimen, one somewhere just above 600° C. and the other around 350° C. Both of these

Figure 21.

breaks were very gradual. The higher indicates the austenite-martensite change, and the lower indicates the martensite-troostite change. A very rapid quench producing martensite would show no break at the lower temperature. This break at about 350° C. would be more pronounced the greater the percentage of troostite remaining.

In Figures 21 and 22, the area just outside of the martensito-troostito boundary is shown at high magnification, 2000 diameters. It is clearly seen that the troostite begins to form evidently in plates, which plates when cut by a plane perpendicularly, show a definite equilateral triangle or, the face of a tetragon imposed within a cube which is

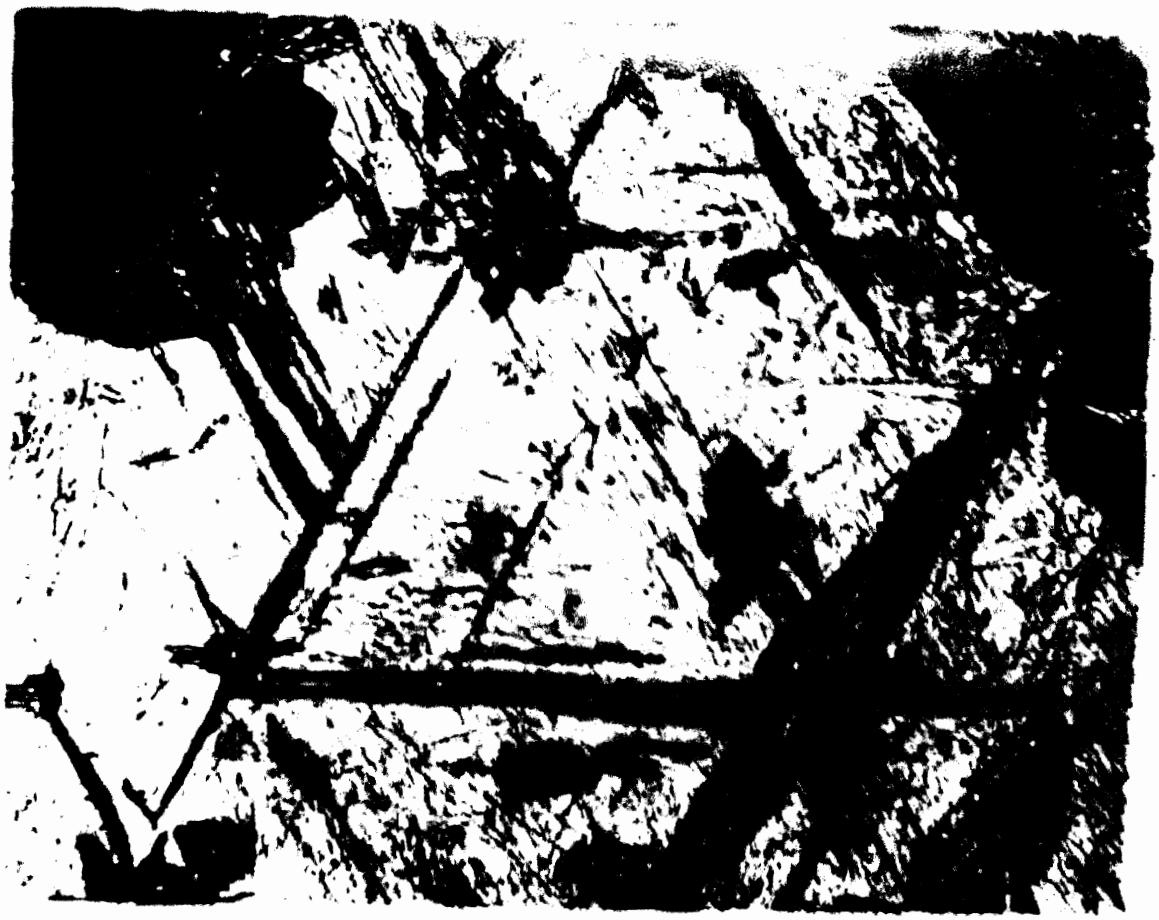


Figure 22.

the 111 plane according to the Miller indices. At this point it is well to consider the fact that in the gamma or face-centered arrangement, parallel to this 111 plane are alternate layers of ferrite atoms and it is between these alternate layers of atoms that the atomic carbon is situated, because the iron atoms in the 111 plane and parallel to it, touch the adjoining iron atoms and leave no room for carbon atoms in these parallel ferrite planes. Therefore, the iron and carbon atoms lie in parallel planes, each plane containing its respective element and no other. In such a system of the composition of steel, there would be relatively few atoms of carbon as compared with iron. Many

cubes would contain no carbon at all. Since these two elements take these positions relative to one another, there would not be perfect homogeneity. Would it not seem reasonable, therefore, to believe that there is an influence of a hereditary nature that would cause the troostite to form along these planes? There would, of course, have to be a coalescence or migration of the carbon atoms because of their quantity and position, but the plated structure of the gamma state would persist and may be termed the "progenitor" of subsequent structures of a platy nature. It would be the higher carbon areas that would first be transformed, the dark areas of Figures 21 and 22; and the lower carbon areas last. It has even been considered that the laminar structure of pearlite may be due to the inceptive segregation in austenite.

CONCLUSIONS - Part 2.

The results of this work check very closely those of previous work of the same nature on C.-0.52 per cent steel impact values. It was found that increasing the temperature before quenching up to 1000° C, increased the impact value - beyond 1000° C., the impact values gradually decreased. Also that drawing from the higher temperature used, 675° C. for ten minutes produced much higher impact value than drawing from the lower temperature 450° C. for thirty minutes.

In conclusion, the author wishes to thank Dr. F. C. Langenbourg of the Watertown Arsenal and R. S. Johnston of the Bureau of Standards, both of whom, as members of The Committee on The Heat Treatment of Carbon Steels of the Engineering Division, National Research Council, assisted by securing the data on the physical properties. The supervision of Professor Charles Y. Clayton of the Missouri School of Mines,and the valuable suggestions and aid of Francis B. Foley, formerly U. S. Bureau of Mines metallurgist, were very much appreciated.

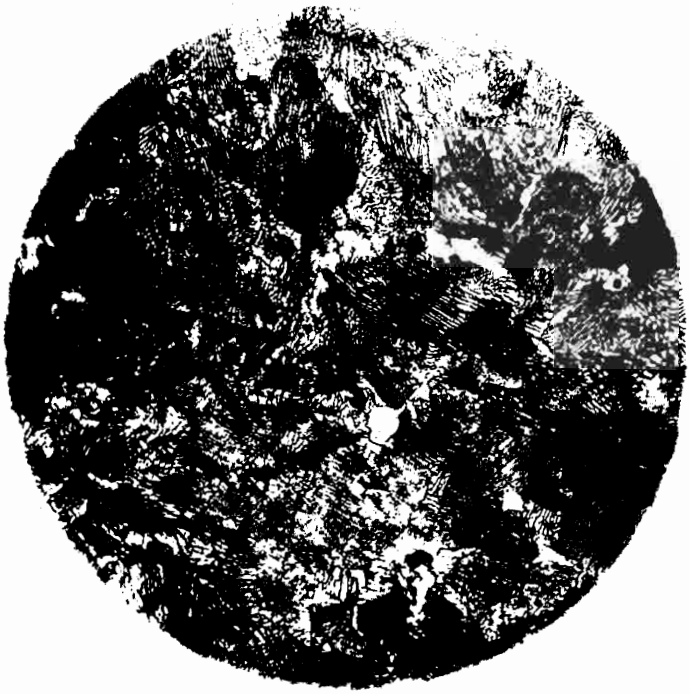


Figure 23;C-C,75 percent. Original 500X.

Figure 24; C-0.75 percent. Original Annealed.

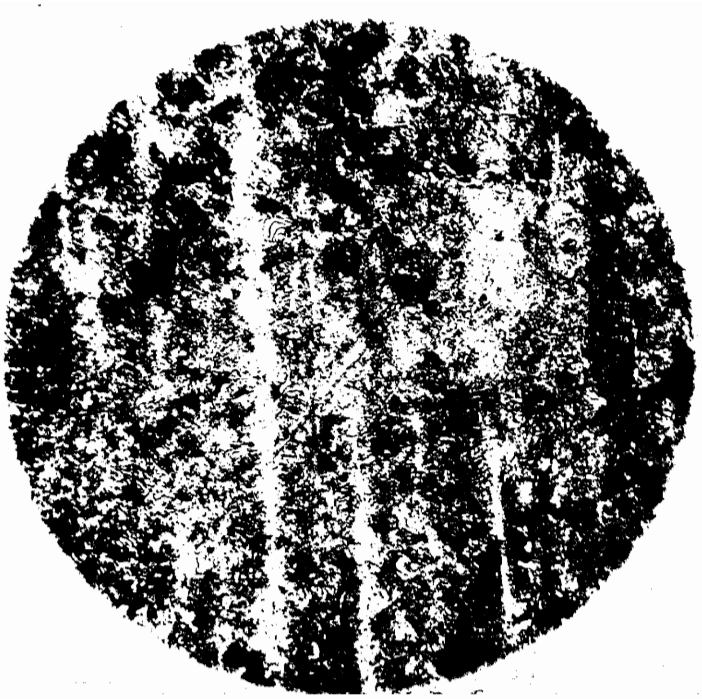


Figure 25; C.-0.75 per cent. Longitudinal of Original,

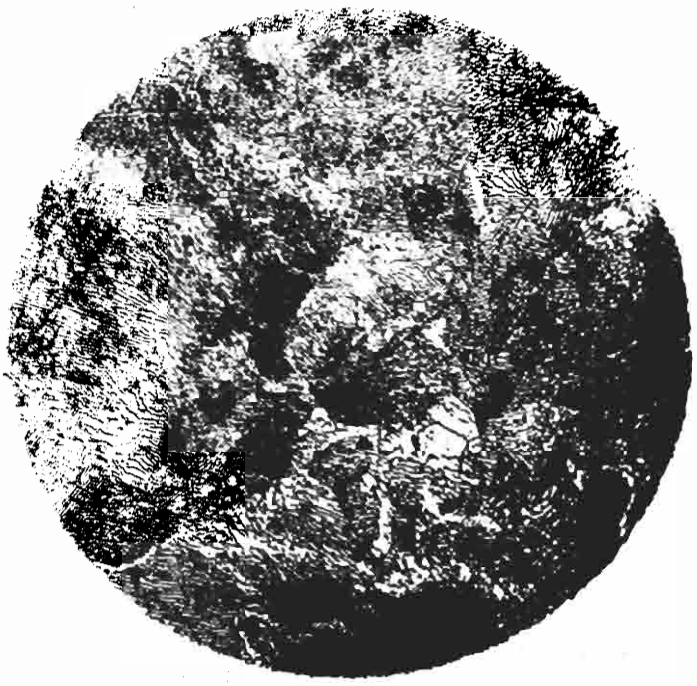


Figure 26; C-0.75 per cent. Air cool after a 30 minute hold at 871°C. 1000 X.

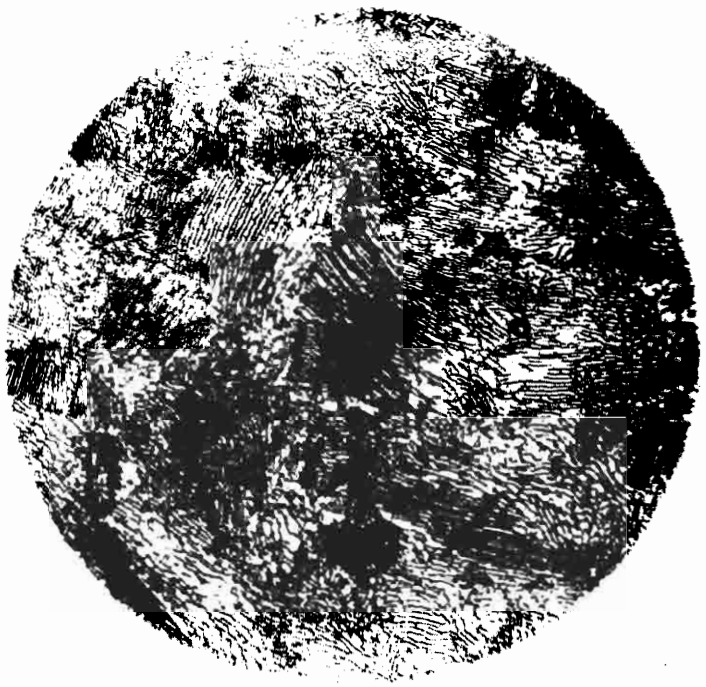


Figure 27; C-0.75 per cent. Lime cool after 30 minute hold at 871°C. 500 X.

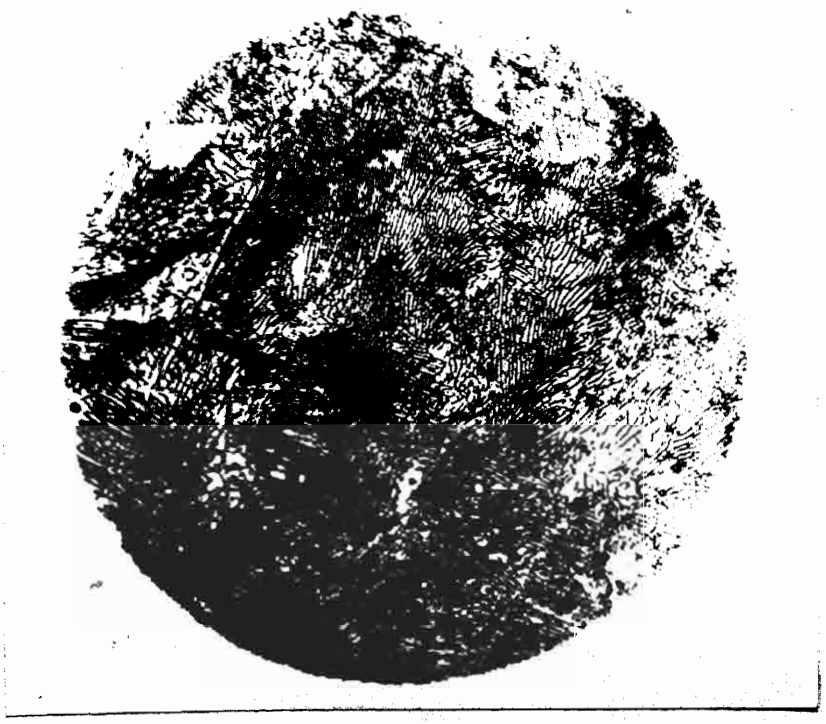


Figure 28; C-0.75 per cent. Furnace cool after 30 minute hold at 871°C. 500 X.

Figure 29; C-0.75 per cent. Double retarded furnace cool after 20 minute hold at 751°C. 500 X.

Figure 30; C-0.75 per cent. Double retarded furnace cool after 1 hour hold at 751°C. 500 X.

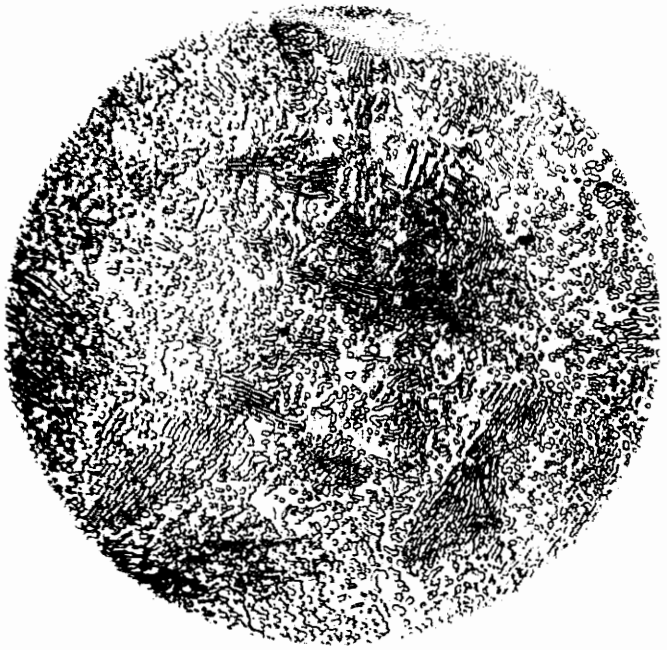


Figure 31; C-0.75 per cent. Double retarded furnace cool after 2 hour hold at 751 C. 500 X.

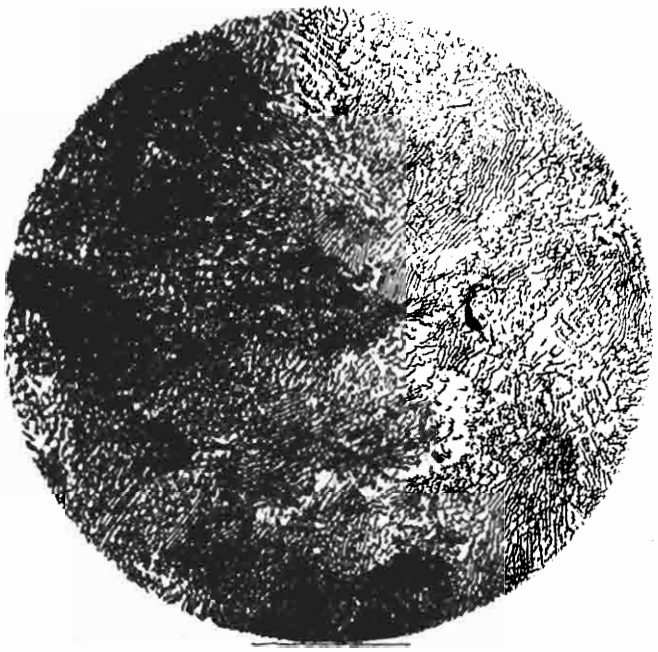


Figure 32; C-0.75 per cent. Plain furnace cool after 20 minute hold at 751 C. 500 X.

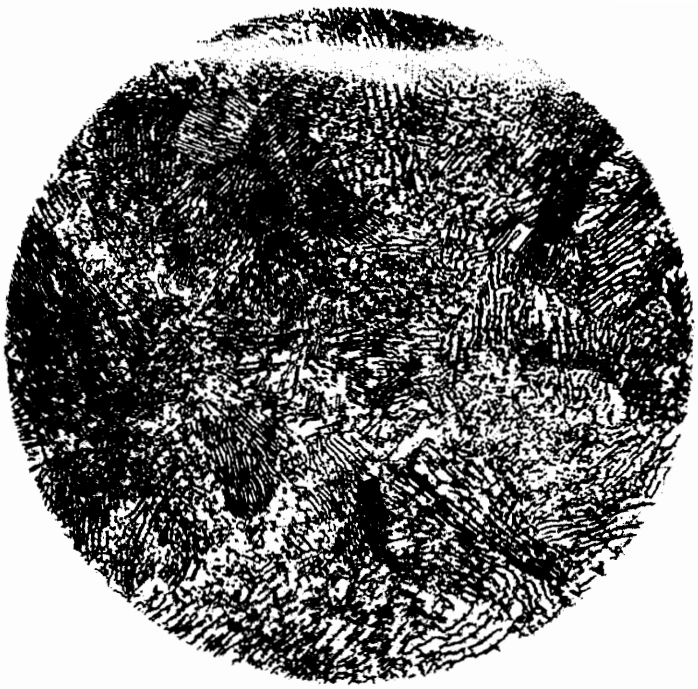


Figure33; C-0.75 per cent. Plain furnace cool after 1 hour hold at 751°C. 500 X.

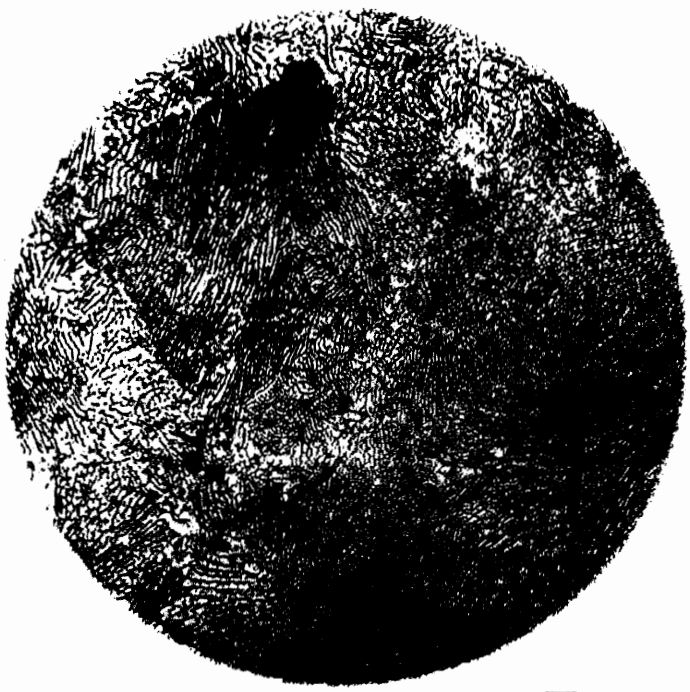


Figure 34; C-0.75 per cent. Plain furnace cool after 2 hour hold at 751°C. 500 X.

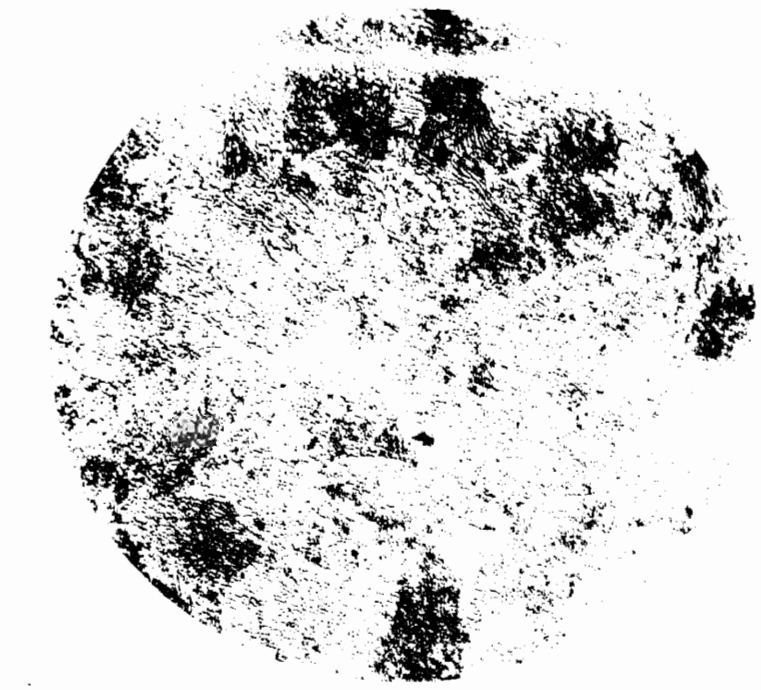


Figure 35; C-0.75 percent. Retarded air cool after 30 minute hold at 751°C. 500 X.

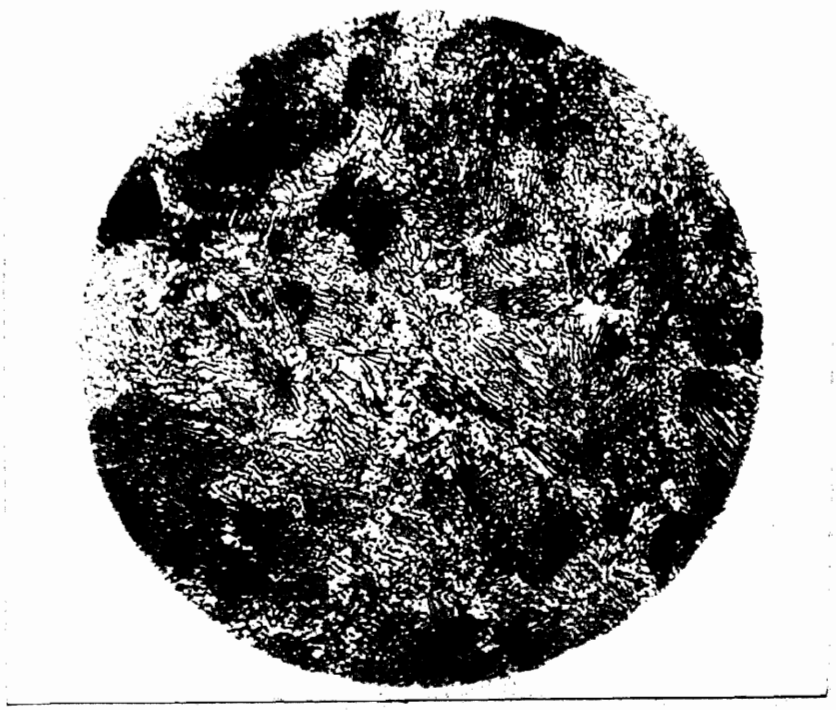


Figure 36; C-0.75 per cent. Retarded air cool after 1 hour hold at 751°C. 500 X.

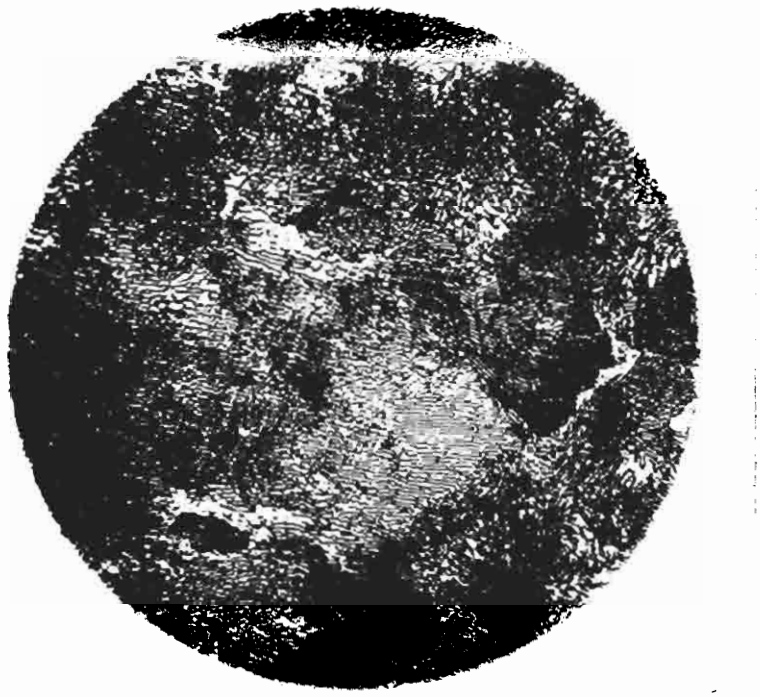


Figure 37; C-0.75 per cent. Retarded air cool after 2 hour hold at 751°C. 500 X.

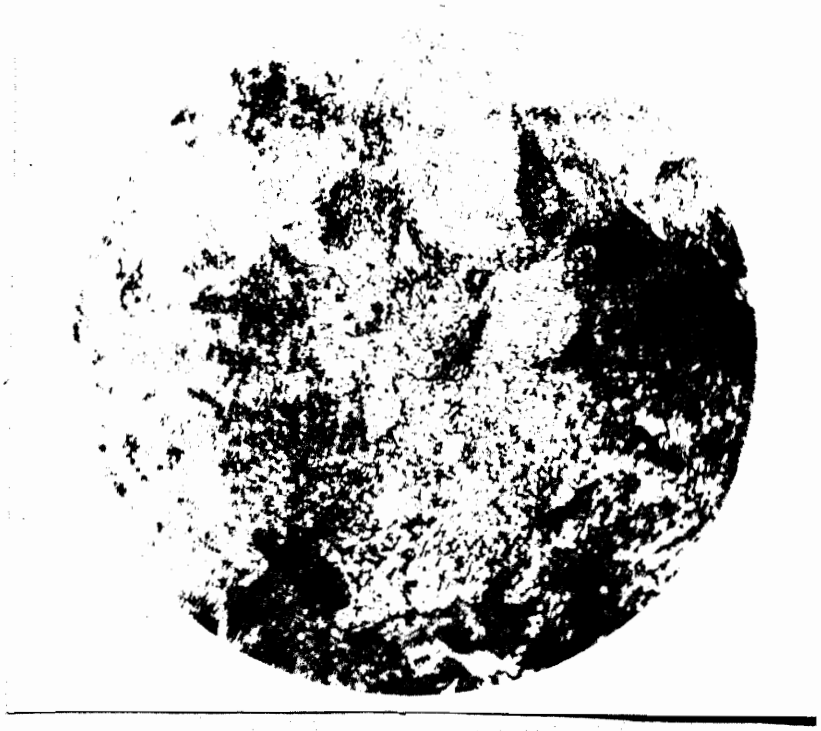


Figure 38; C-0.75 per cent. Plain air cool after 20 minute hold at 751°C. 500 X.

Figure 39; C-0.75 per cent. Plain air cool after 1 hour hold at 751°C. 500 X.

Figure 40; C-0.75 per cent. PLain air cool after 2 hour hold at 751°C. 500 X.

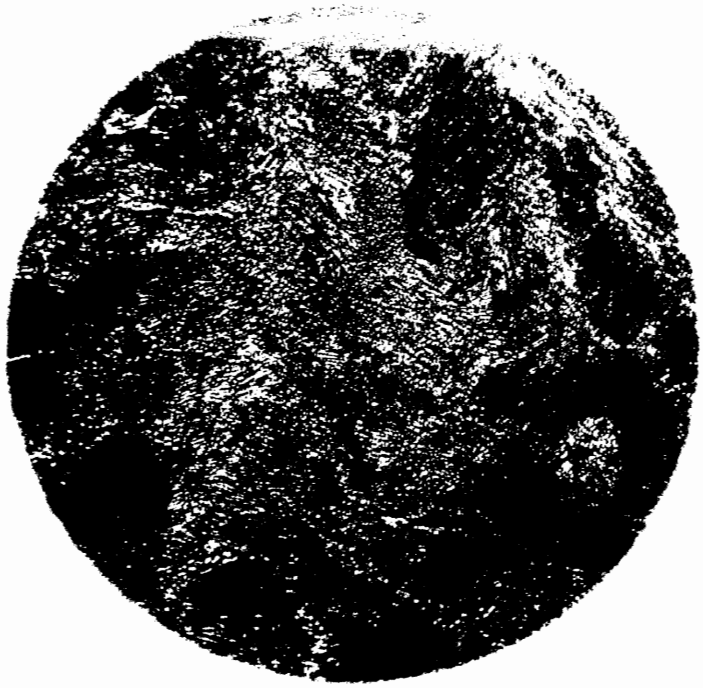


Figure 41; C-0.75 percent. Accelerated air cool after 20 minute hold at751°C. 500 X.

Figure 42; C-0.75 per cent. Accelerated air cool after 1 hour hold at 751°C. 500 X.

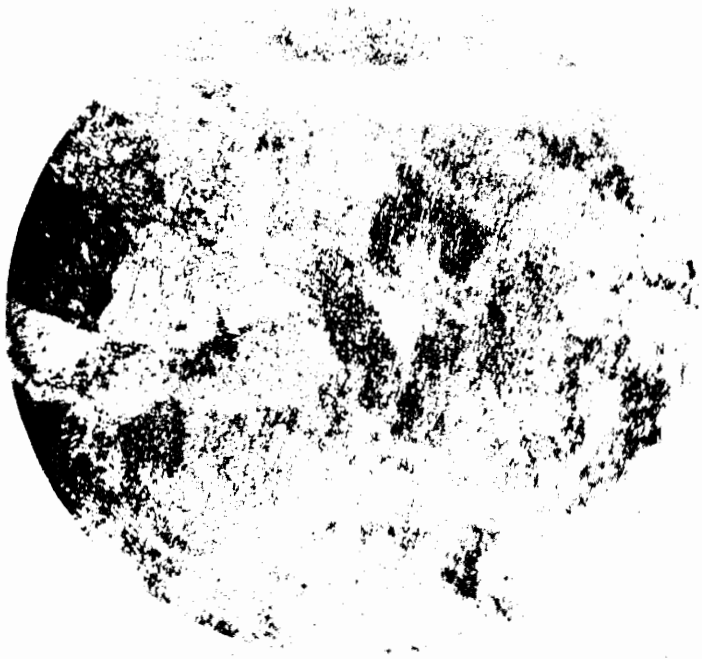


Figure 43; C-0.75 per cent. Accelerated air cool after 2 hour hold at 751°C. 500 X.

Figure 44; C-0.75 per cent. Air cool after 30 minute hold at 871°C. 1000 X.

Figure 45; C-0.75 per cent. Line cool after 30 minute hold at 871°C. 1000 X.

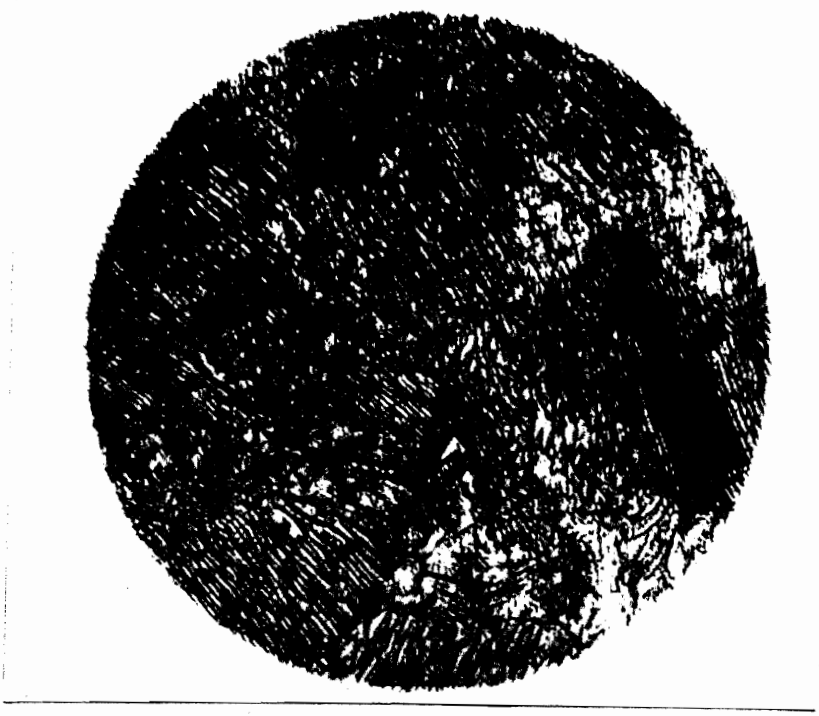


Figure 46; C-0.75 percent. Furnace cool after 30 minute hold at 871°C. 1000 X.

Figure 47; C-0.75 per cent. Double retarded furnace cool after 20 minute hold at 751°C. 2000 X.

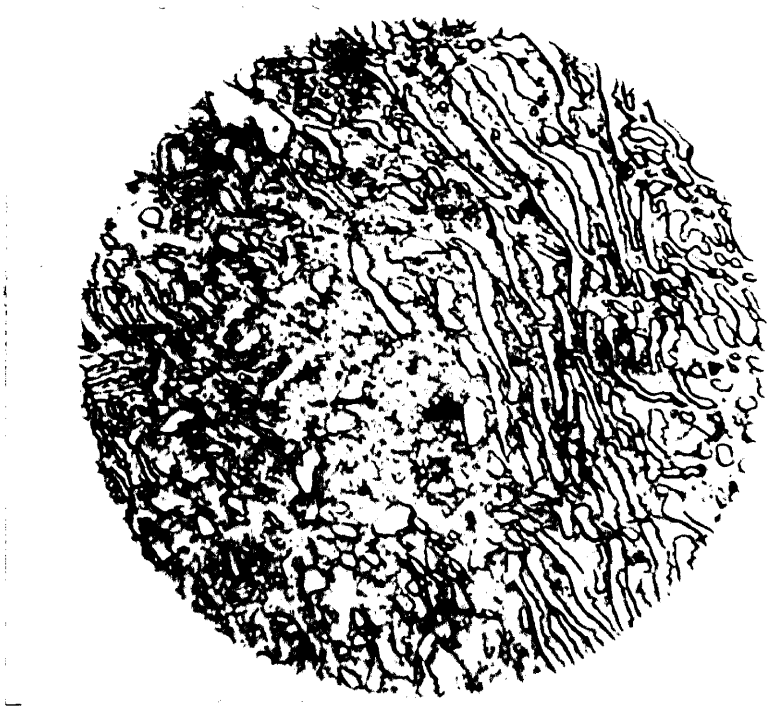


Figure 48; C-0.75 percent. Double retarded furnace cool after 1 hour hold at 751°C. 2000 X.

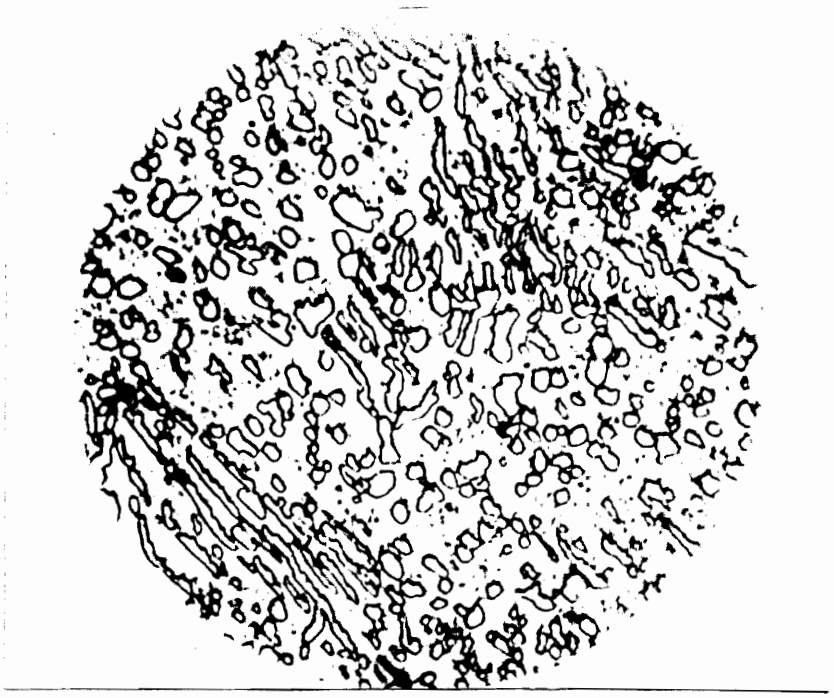


Figure 49; C-0.75 per cent. Double retarded furnace cool after 2 hour hold at 751°C. 2000 X.

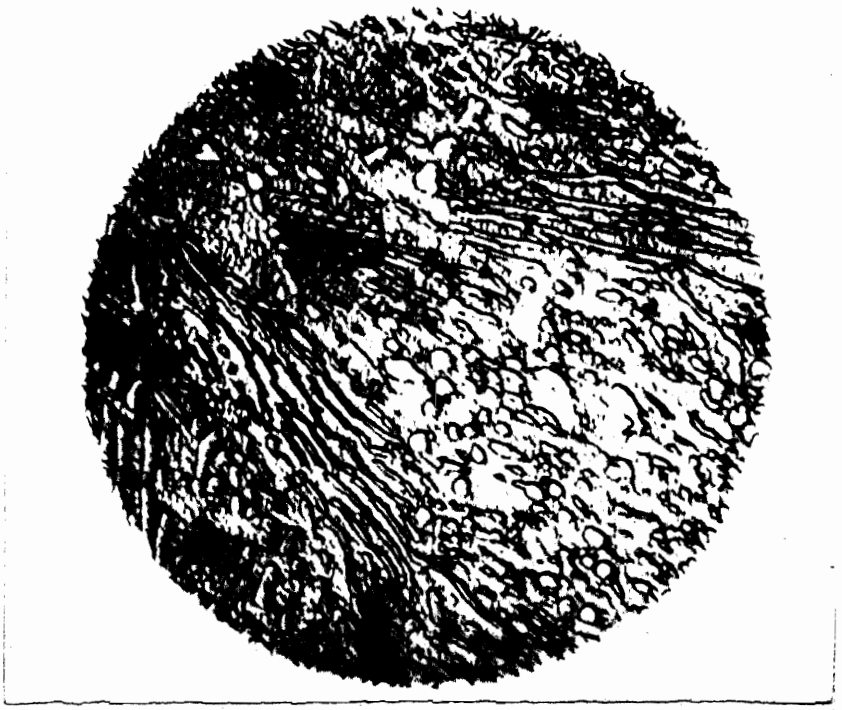


Figure 50; C-0.75 per cent.Plain furnace cool after 20 minute hold at 751°C. 2000 X.

Figure51; C-0.75 per cent.Plain furnace cool after 1 hour hold at 751°C. 2000 X.

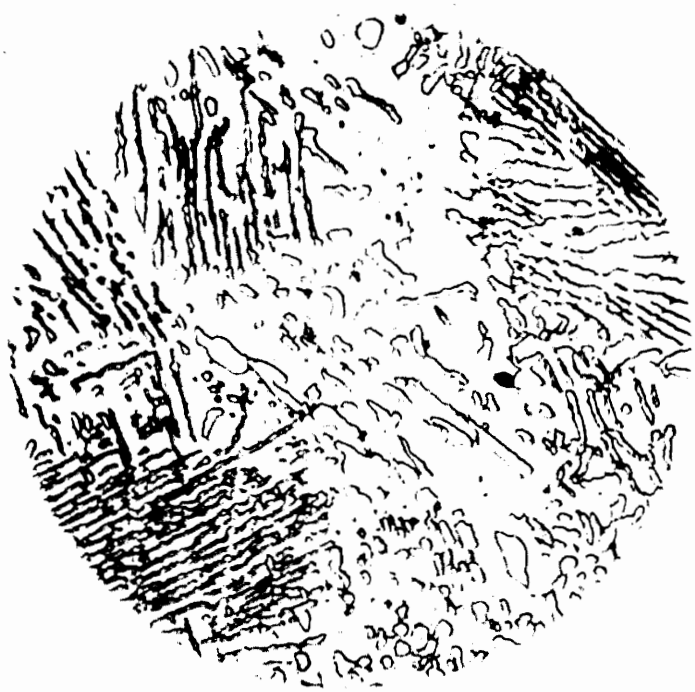


Figure 52; C-0.75 per cent. Plain furnace cool after 2 hour hold at 751°C. 2000 X.

Figure 53, C-0,75 per cent. Retarded air cool after 20 minute hold at 751°C. 2000 X.

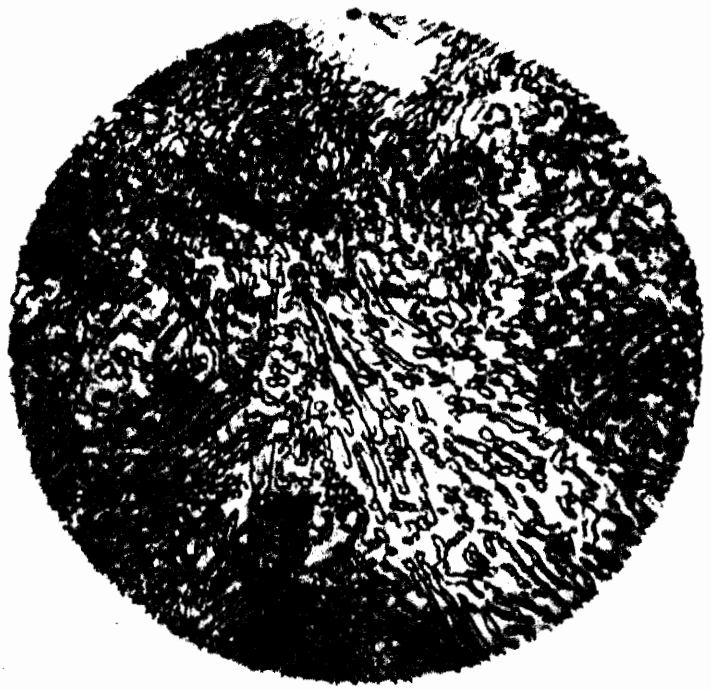


Figure 54; C-0.75 per cent. Retarded air cool after 1 hour hold at 751°C. 2000 X.

Figure 55; C-0.75 per cent. Retarded air cool after 2 hour hold at 751°C. 2000 X.

Figure 56; C-0.75 per cent. Plain air cool after 20 minute hold at 751°C. 2000 X.

Figure 57; C-0.75 per cent. Plain air cool after 1 hour hold at 751°C. 2000 X.

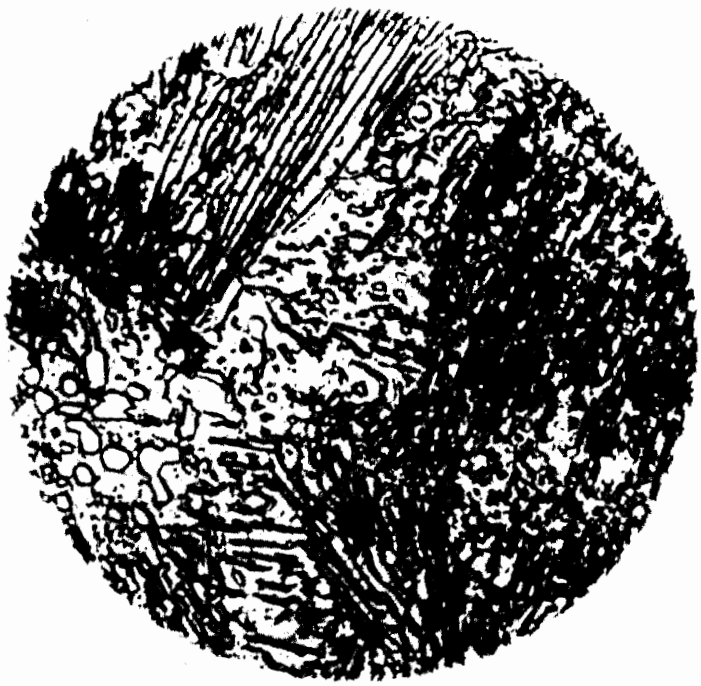


Figure 58; C-0.75 per cent. Plain air cool after 2 hour hold at 751°C. 2000 X.

Figure 59; C-0.75 per cent. Accelerated air cool after 20 minute hold at 751°C. 2000 X.

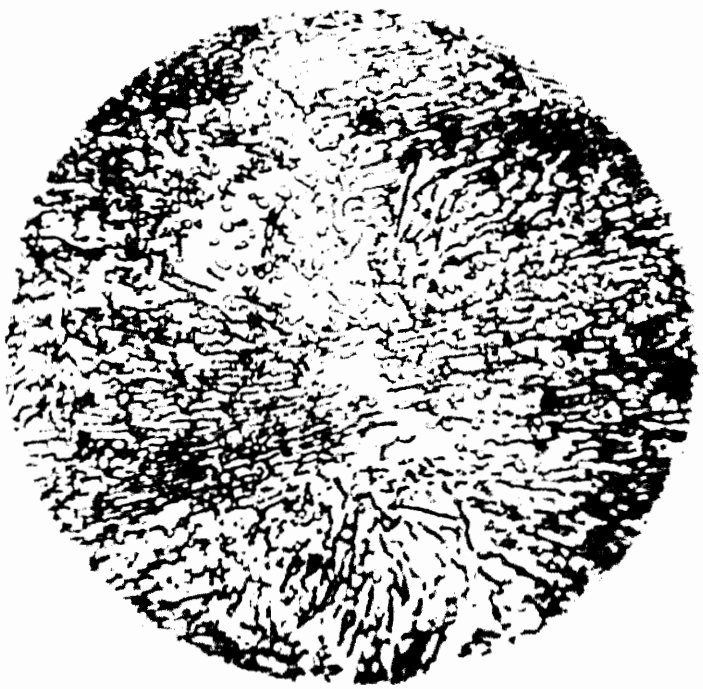


Figure 60; C-0.75 per cent. Accelerated air cool after 1 hour hold at 751°C. 2000 X.

Figure 61; C-0.75 per cent. Accelerated air cool after 2 hour hold at 751°C. 2000 X.

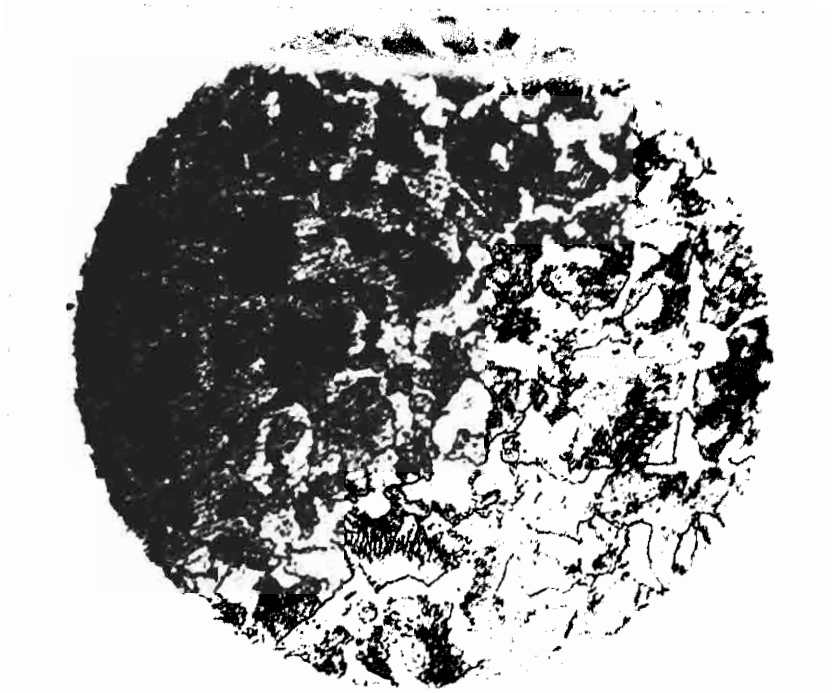


Figure 62; C-0.52 per cent. Original. 500 X.

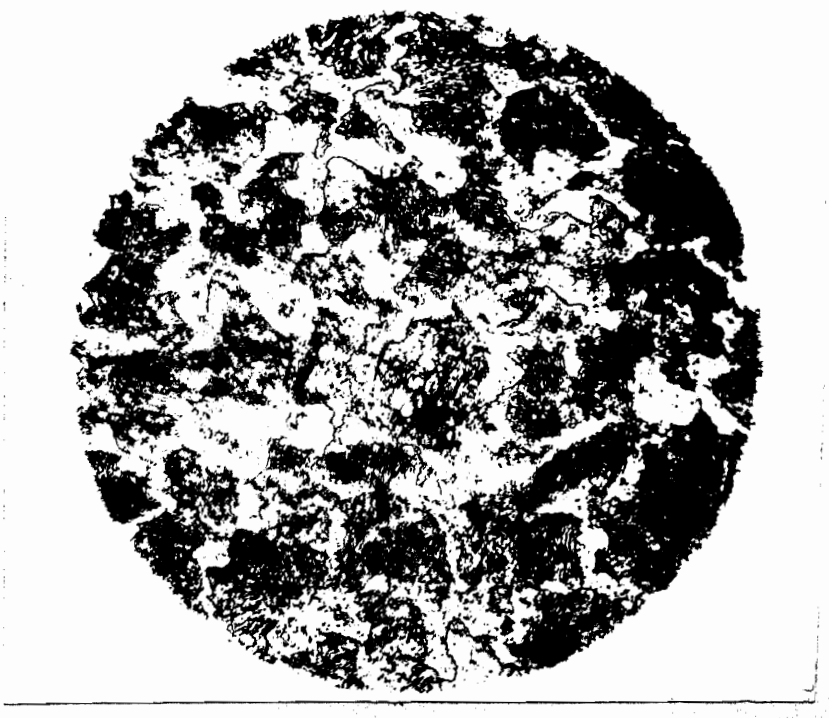


Figure 63; C-0.52 per cent. Original annealed. 500 X.

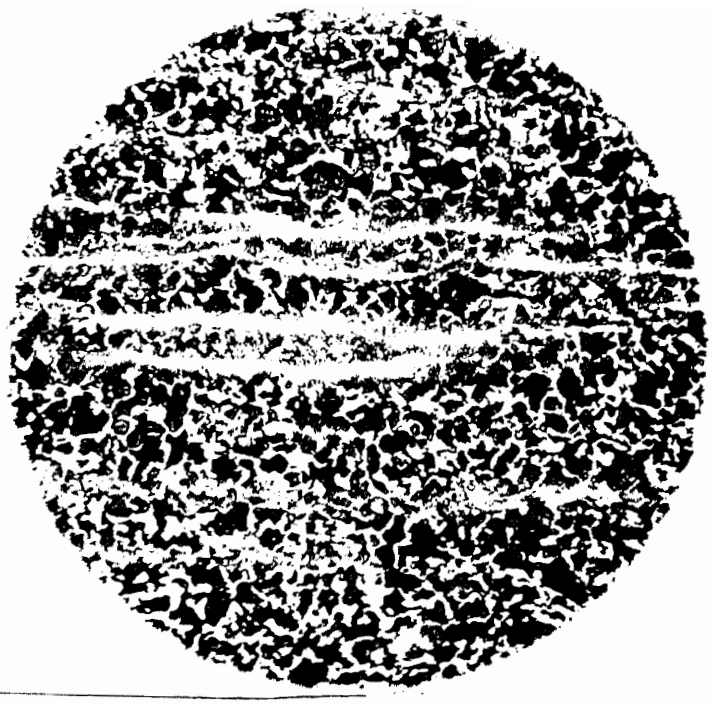


Figure 64; C-0.52 per cent. Original, longitudinal. 150 X.

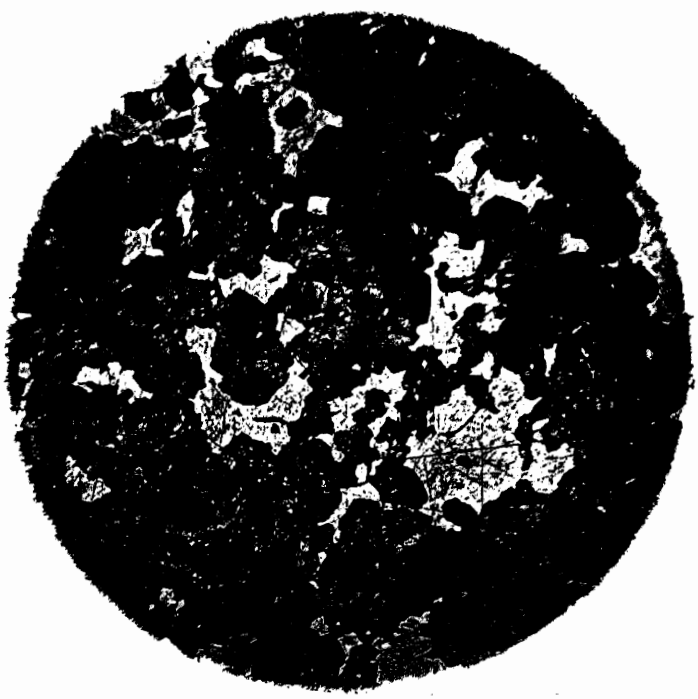


Figure 65; C-0.52 per cent. Quenched after 10 minute hold at 845°C.-150 X.

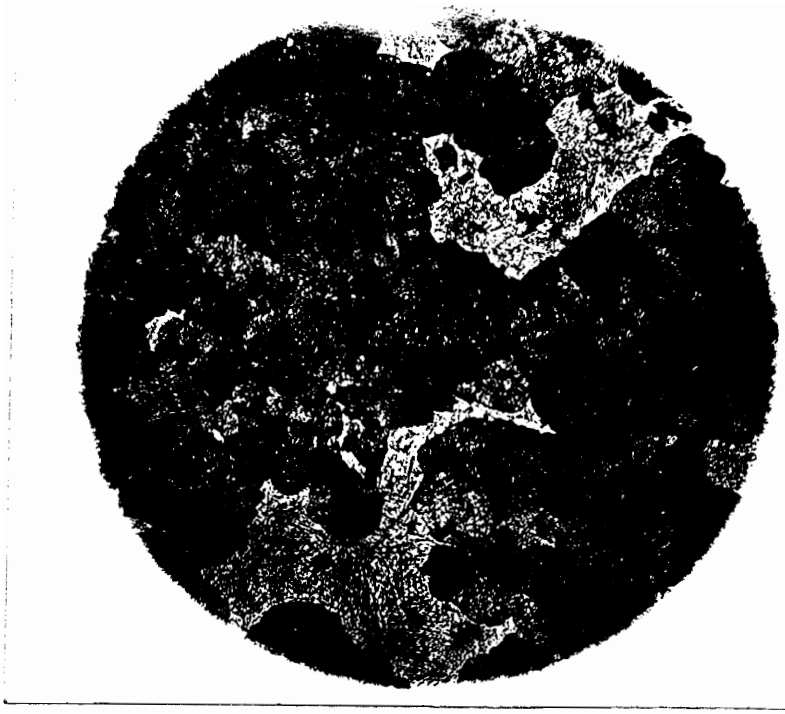


Figure 66; C-0.52 per cent. Quenched after a 10 minute hold at 975°C. 150 X.

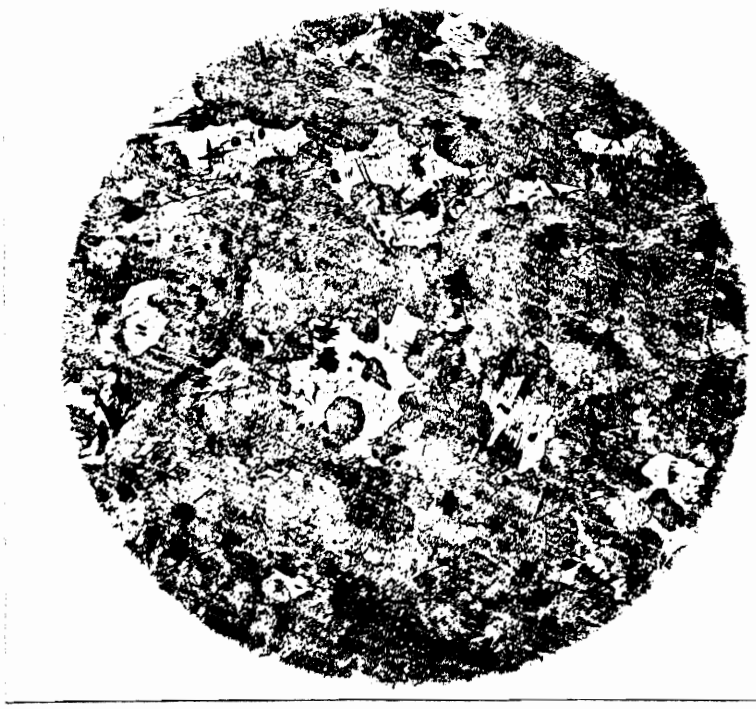


Figure 67; C-0.52 per cent. Quenched after a 10 minute hold at 1040°C. 150 X.

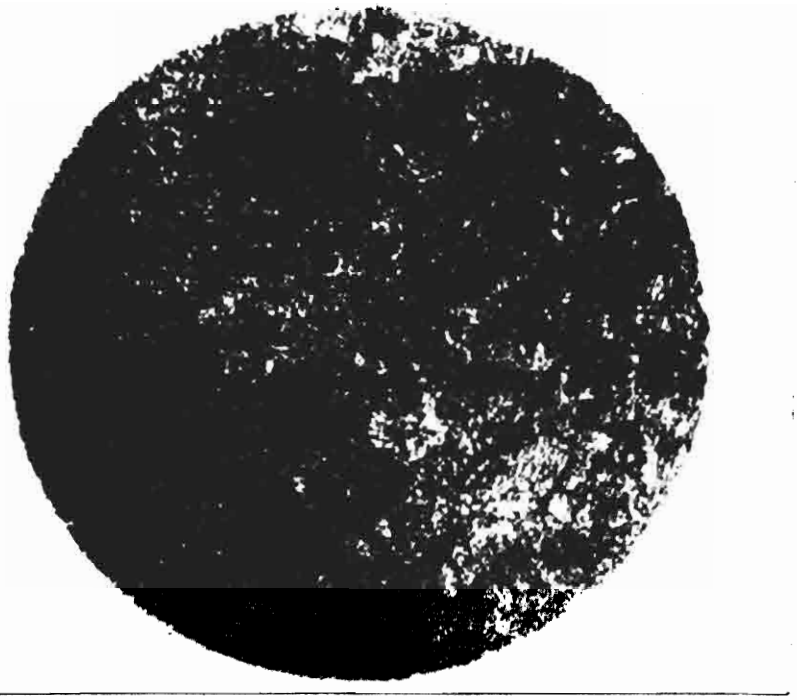


Figure 68; C-0.52 per cent. Quenched after a 10 minute hold at 845°C.-Drawn at 450°C. for 30 minutes. 500 X.

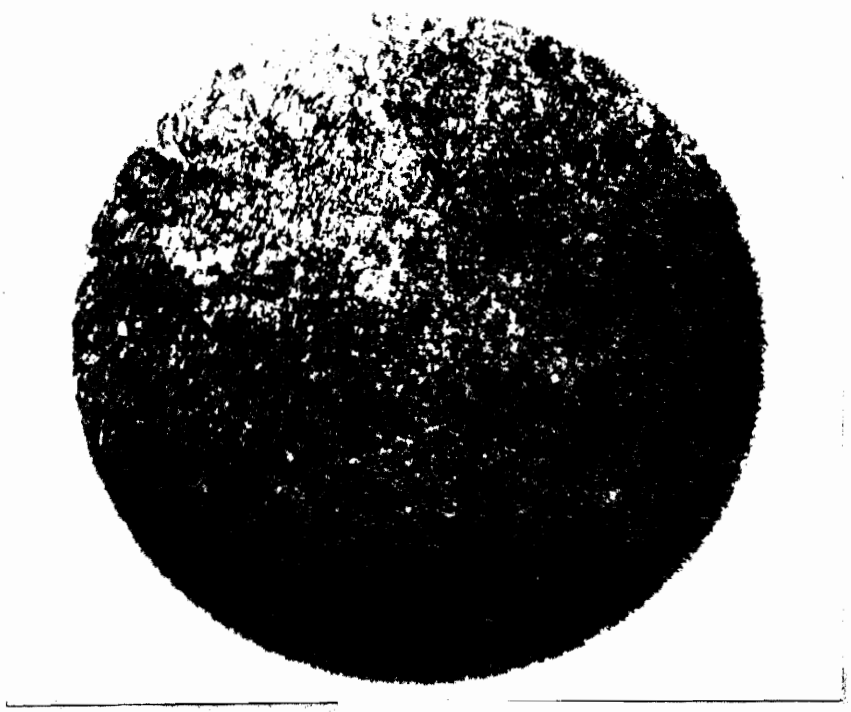


Figure 69; C-0.52 per cent. Quenched after a 10,minute hold at 845°C.-Drawn at 675°C. for 10 minutes. 500 X.

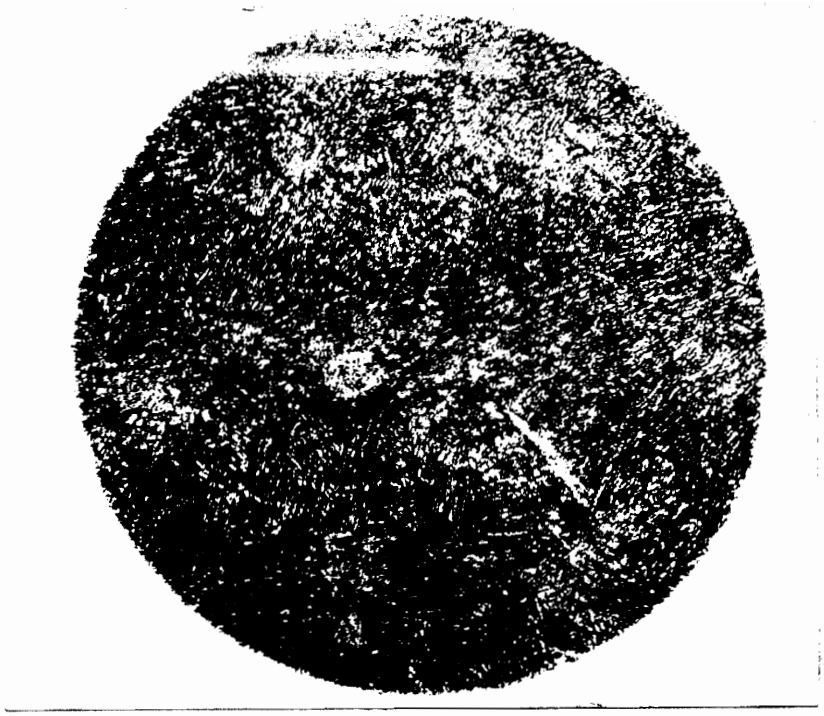


Figure 70; C-0.52 per cent. Quenched after a10 minute hold at 975°C.-Drawn at 450°C for 30 minutes. 500 X.

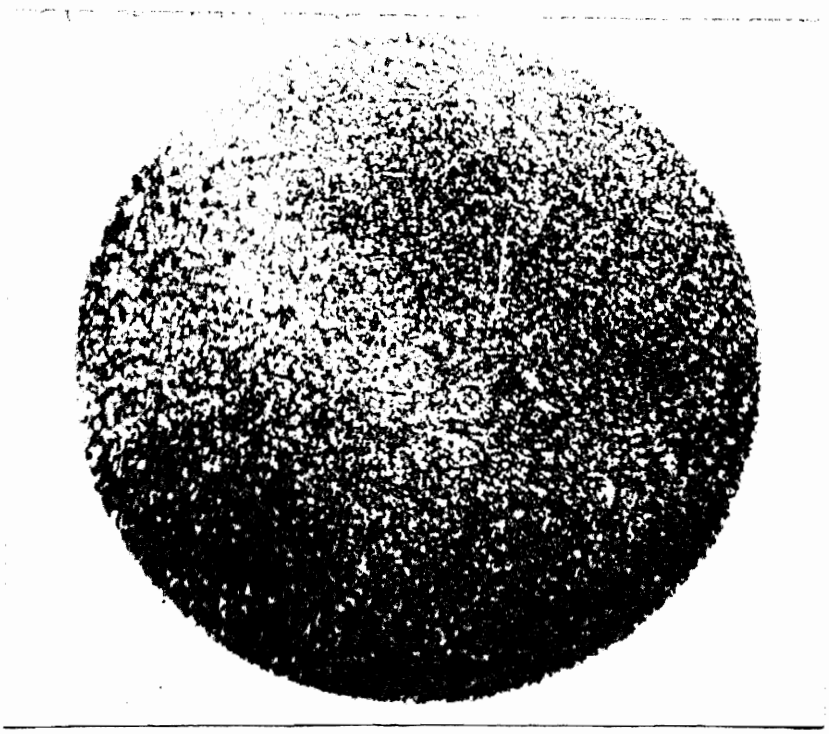


Figure 71; C-0.5~ per cent. Quenched after a 10 minute hold at 975°C.-Drawn at 675°C for 10 minutes. 500 X.

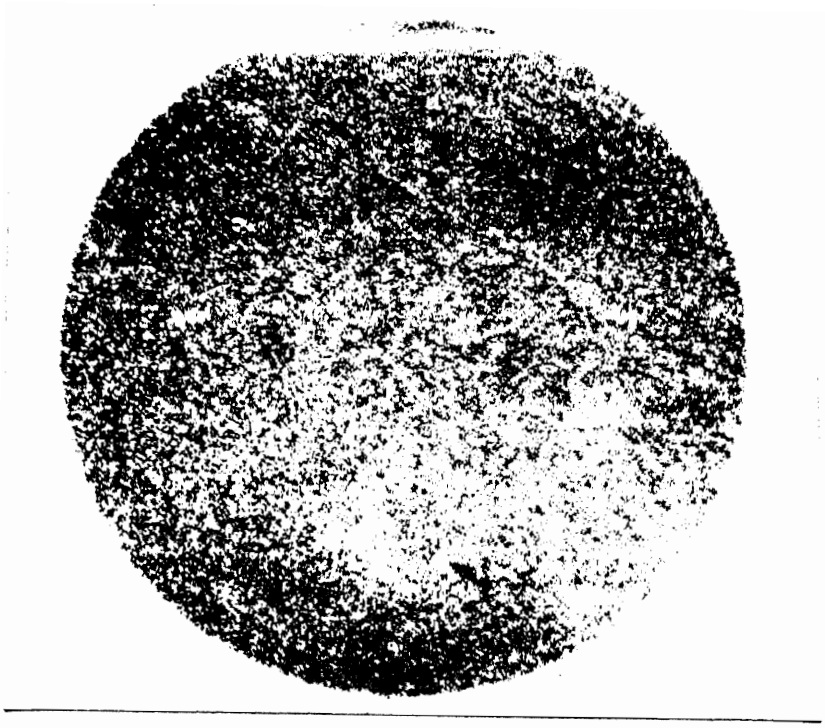


Figure 72, C_3C.52 per cent. Quenched after a 10 minute hold at 1040 C.-Drawn at 450°C for 30 minutes. 500 X.

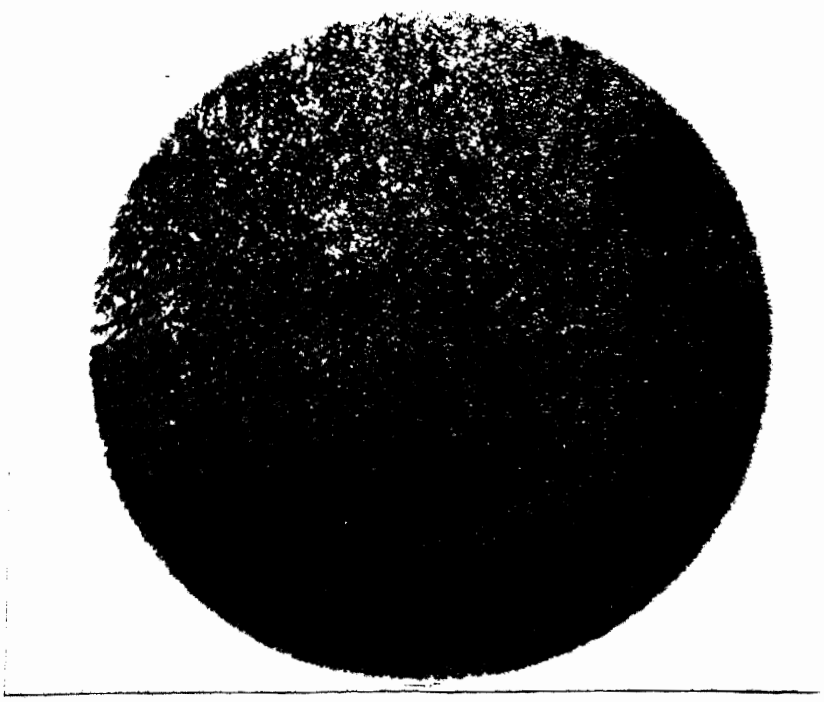


Figure 73; C-0.52 per cent. Quenched after a 10 minute hold at 1040°C.-Drawn at 675°C for 10 minutes. 500 X.

Figure 74; C-0.52 per cent. Original. 2000 X.

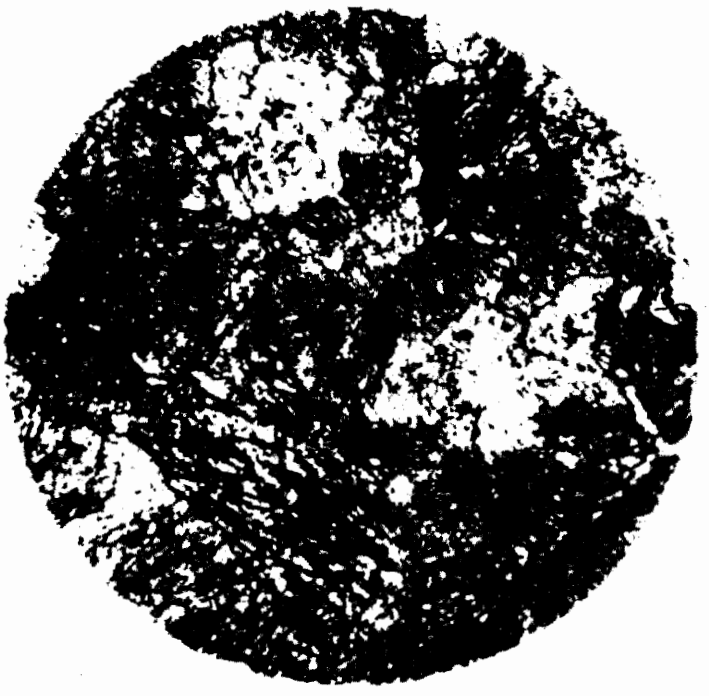


Figure 75; C-0.52 per cent. Quenched after a 10 minute hold at 845°C.-Drawn at 450°C. for 30 minutes. 2000 X.

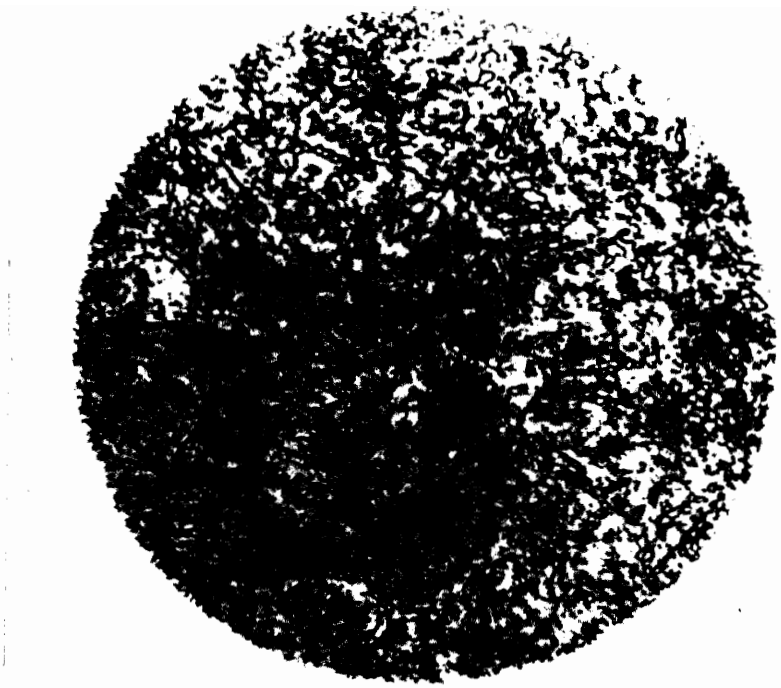


Figure 76; C-C.52 per cent. Quenched after a 10 minute hold at 845°C.-Drawn at 675°C. for 10 minutes. 2000 X.

Figure 77; C-0,52 per cent. Quenched after a 10 minute hold at 975°C.-Drawn at 450°C for 30 minutes. 2000 X.

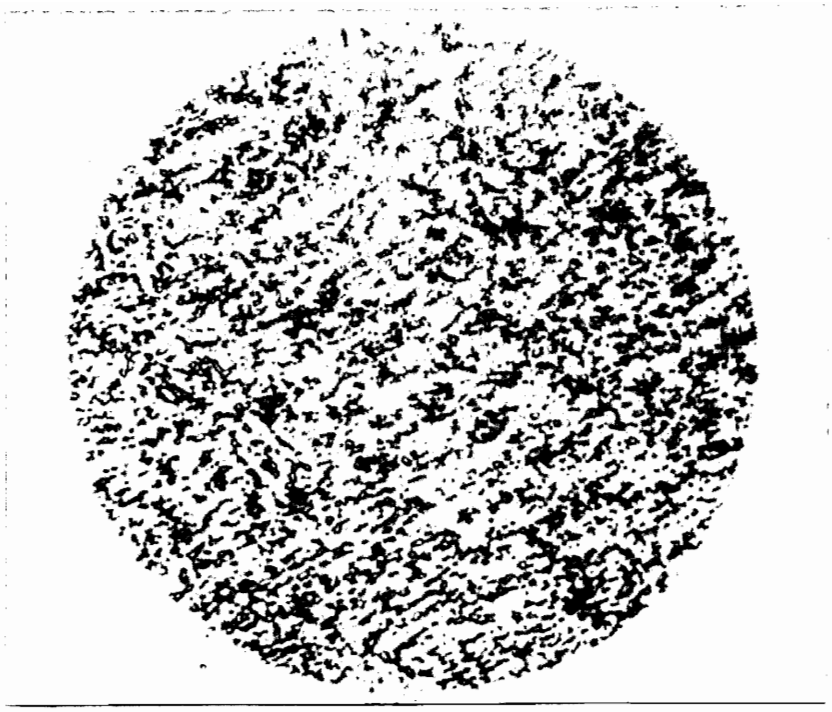


Figure 78; C-0.52 per cent. Quenched after a 10 minute hold at 975°C.-Drawn at 675°C. for 10 minutes. 2000 X.

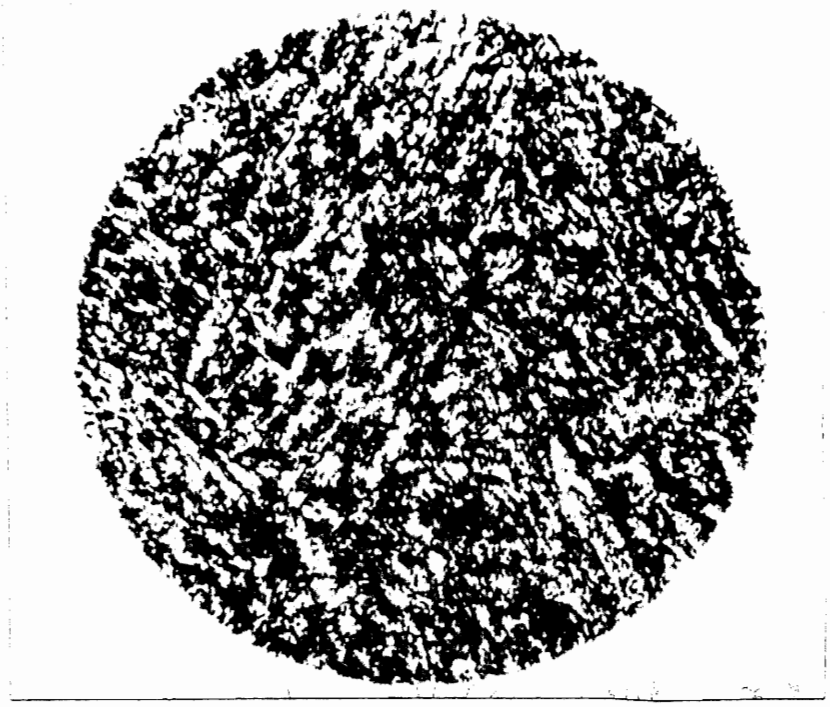


Figure 79; C-0.52 per cent. Quenched after a 10 minute hold at 1040°C.-Drawn at 450°C for 30 minutes. 2000 X.

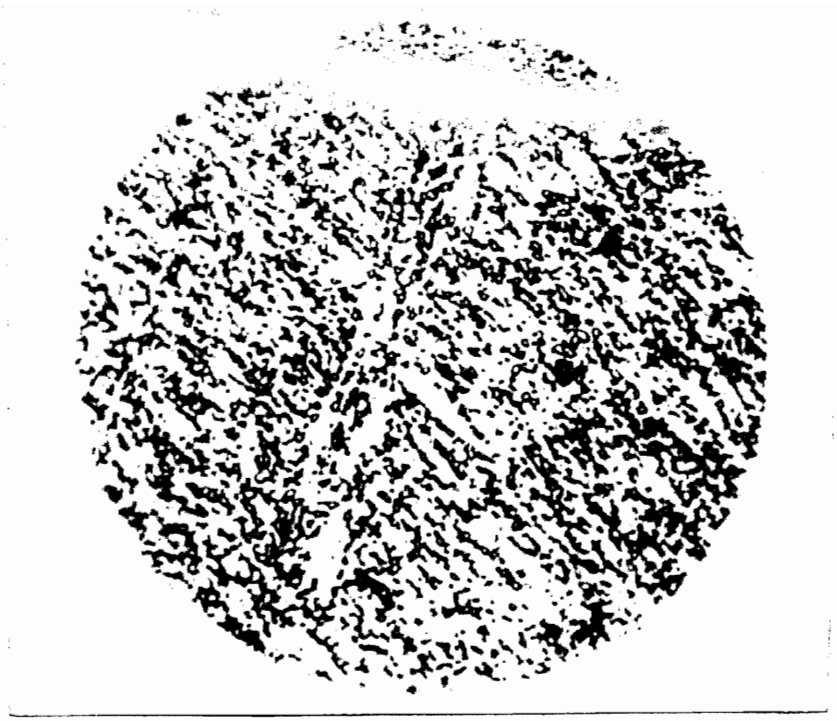


Figure 80; C.-0.52 per cent. Quenched after a 10 minute hold at 1040°C.-Drawn at 675°C. for 10 minutes. 2000 X.

INDEX.

TABLE OF PHYSICAL VALUES.

Heat-treatment.			Proportional Limit.			Yield Point.			Tensile Strength.			Stress at Rupture.			Extension.			Reduction of Area.			Impact Value-Charpy.			Brinell Number.		
Cooling Method	Rate of per Second 1515888		Lb. per Sq. In.	Diff.	% of Obs.	Lb. per Sq. In.	Diff.	% of Obs.	Lb. per Sq. In.	Diff.	% of Obs.	Lb. per Sq. In.	Diff.	% of Obs.	Per Cent.	Diff.	% of Obs.	Per Cent.	Diff.	% of Obs.	Ft-Lb.	Diff.	% of Obs.	B.H.N.	Diff.	% of Obs.
A	0.00667	O	40,000			40,250			89,600			127,000			19.0	-0.35		35.0	-9.1		1.845			180		
		C	34,194	-5,806	14.5	45,758	+5,508	13.7	92,382	+2,982	3.3	120,711	-6,289	4.9	18.65		1.84	25.9		26.0	.88	-.965	52.3	185	+5	2.8
1A	0.00892	O	39,000			39,500			94,600			127,000			20.0			30.0			1.52			187		
		C	34,525	-4,475	11.4	45,961	+6,461	16.3	93,099	-1,501	1.6	121,136	-5,864	4.6	18.65	-1.35	6.75	26.3	-3.7	12.3	.96	-.56	36.8	186	-1	0.5
2A	0.00718	O	41,000			41,800			86,600			144,800			31.0			50.0			1.99			174		
		C	34,126	-6,874	16.7	45,714	+3,914	9.3	92,474	+5,874	6.8	120,813	-23,987	16.5	18.65	-12.35	39.83	26.0	-24.0	28.0	.90	-1.09	54.8	187	+13	7.5
C	0.05358	O	43,500			43,920			97,400			142,000			21.0			37.1			2.72			192		
		C	37,460	-6,040	13.8	47,769	+3,849	8.7	97,679	+279	0.3	125,685	-16,315	11.5	18.65	-2.35	11.19	28.7	-8.3	22.4	1.61	-1.11	40.8	199	+7	3.6
1C	0.05136	O	42,000			43,700			100,000			137,000			19.5			33.1			1.99			194		
		C	37,368	-4,632	11.0	47,713	+4,013	9.2	97,536	-2,464	2.5	125,524	-11,476	8.4	18.65	-0.85	4.36	28.7	-4.3	13.0	1.60	-.39	19.5	198	+4	2.1
2C	0.05437	O	41,000			41,900			101,000			136,000			18.5			30.1			1.87			204		
		C	37,461	-3,539	8.6	47,770	+5870	14.0	97,681	-3,314	3.3	125,741	-10,259	7.5	18.65	+0.15	0.81	28.75	-1.25	4.3	1.62	-.25	13.4	199	-5	2.5
E	0.52201	O	50,500			51,000			110,000			155,000			19.0			35.0			3.06			212		
		C	44,866	-5,634	11.1	52,333	+1,333	2.6	109,237	-763	0.7	141,987	-13,019	8.3	18.65	-0.35	1.84	32.2	-2.8	8.0	3.13	+.07	2.3	223	+11	5.2
1E	0.50609	O	50,000			51,700			113,000			152,000			17.0			30.0			2.28			219		
		C	44,724	-5,276	10.5	52,246	+546	1.0	109,016	-3,984	3.5	141,619	-10,381	6.8	18.65	+1.65	9.71	32.1	+2.1	7.0	3.10	+.82	36.0	222	+3	1.4
2E	0.53205	O	47,000			47,350			111,500			149,000			15.0			29.0			2.11			223		
		C	44,956	-2,044	4.3	52,389	+5039	10.6	109,377	-2,123	1.9	142,216	-6,784	4.5	18.65	+3.65	24.38	32.2	+3.2	11.0	3.15	+1.04	49.3	223	0	0
F	0.75113	O	48,000			48,400			108,700			154,000			18.0			35.0			3.61			209		
		C	46,664	-1,336	2.8	53,441	+5,041	10.4	112,043	+3,343	3.0	146,774	-7,226	4.7	18.65	+0.65	3.61	32.8	-2.2	6.3	3.48	-.13	3.6	228	+19	9.1
1F	0.73451	O	56,000			56,900			116,500			158,000			17.0			32.0			2.16			223		
		C	46,547	-9,453	16.8	53,369	-3,531	6.2	111,860	-4,640	3.9	146,453	-11,547	7.3	18.65	+1.65	9.71	32.7	+0.7	2.2	3.45	+1.29	59.7	228	+5	2.2
2F	0.85120	O	54,500			54,800			116,400			157,000			14.0			31.0			2.16			213		
		C	47,383	-7,167	13.1	53,854	-946	1.7	113,087	-3,313	2.8	148,634	-8,366	5.3	18.65	+4.65	33.21	33.0	+2.0	6.4	3.61	+1.45	67.1	230	+17	8.0
G	1.09210	O	47,000			50,000			110,600			147,500			16.0			29.0			2.94			219		
		C	48,753	+1,753	3.7	54,729	+4,729	9.4	115,304	+4,704	4.2	152,694	+5,194	3.5	18.65	+2.65	16.56	33.4	+4.4	15.2	3.88	+.94	32.0	233	+14	6.4
1G	1.10667	O	53,500			54,300			116,600			163,500			15.0			34.0			1.895			235		
		C	48,819	-4,681	8.7	57,769	+469	0.9	115,406	-1,194	1.0	152,926	-10,514	6.5	18.65	+3.65	24.33	33.4	-0.6	1.7	3.89	+1.995	105.3	234	-1	0.4
2G	1.08496	O	57,000			58,000			124,000			162,600			17.0			29.0			2.98			245		
		C	48,706	-8,294	14.5	54,700	-3,300	6.0	115,231	-8,769	7.0	152,581	-10,019	6.2	18.65	+1.65	9.71	33.4	+4.4	15.0	3.87	+.89	29.9	233	-12	4.9
ANNEALED ONLY.																										
A8	0.72490	O	56,000			58,200			123,700						16.5			25.0			2.42			245		
		C	46,479	-9,521	17.0	53,327	-4,873	8.4	111,754	-11,946	9.7	146,567	=	=	18.65	+2.15	13.0	32.7	+7.7	30.8	3.44	+1.02	42.1	227	-18	7.3
L8	0.29400	O	49,000			49,700			114,650			143,000			16.0			24.0			2.025			223		
		C	42,441	-6,559	13.4	50,839	+1,139	2.3	105,452	-9,198	8.0	136,002	-6,998	7.9	18.65	+2.65	16.6	31.3	+7.3	30.4	2.65	+.625	30.9	216	-7	3.1
F8	0.02510	O	39,000			39,800			107,800						16.5			18.0			1.615			212		
		C	36,003	-2,997	7.7	46,872	+7,072	18.8	95,405	-12,395	11.5	123,260	=	=	18.65	+2.15	13.0	27.7	+9.7	53.9	1.30	-.315	19.5	193	-19	9.0